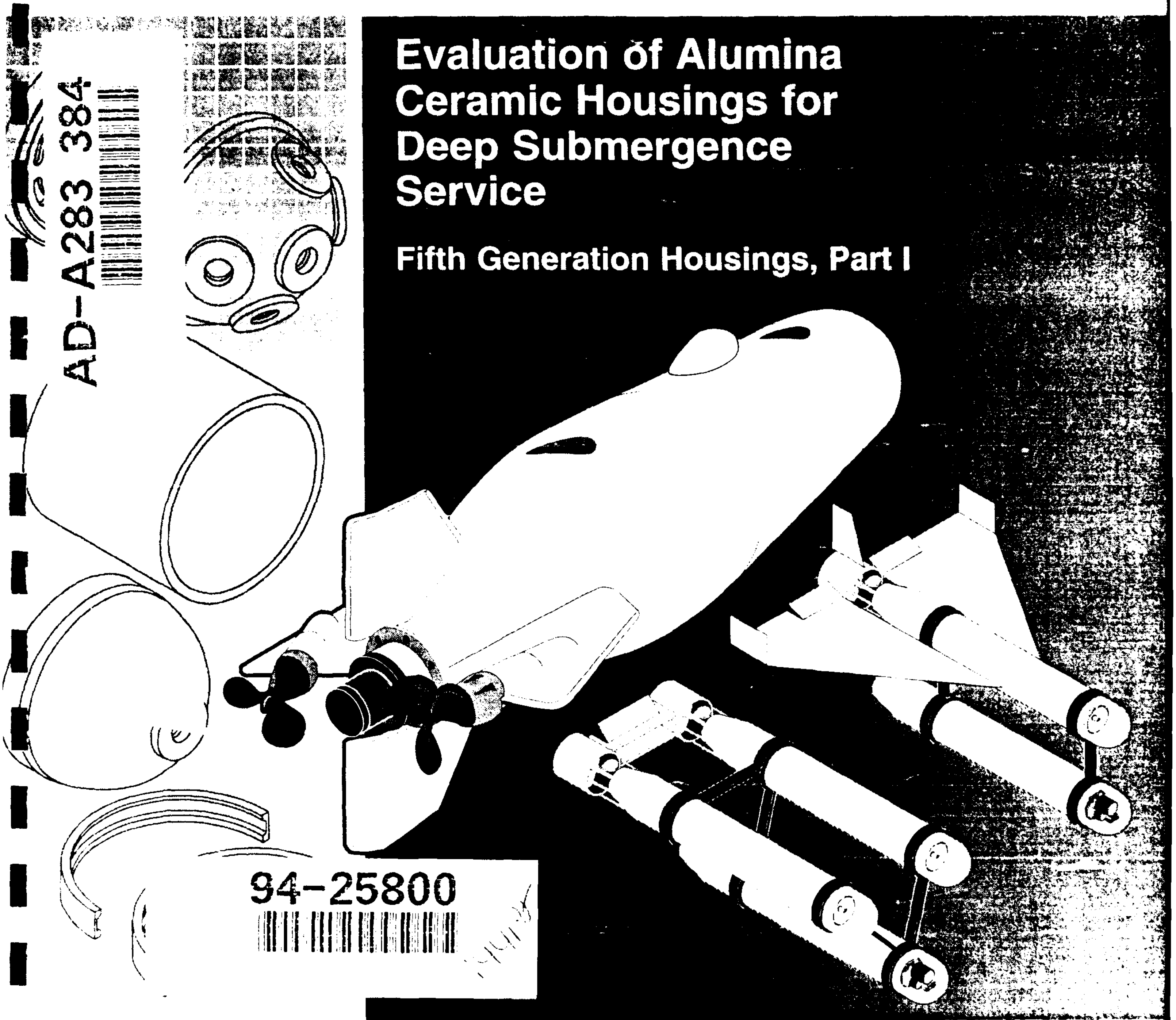
Naval Command, Control and Ocean Surveillance Center
RDT&E Division San Diego, CA 92152-5001

Evaluation of Alumina Ceramic Housings for Deep Submergence Service

Fifth Generation Housings, Part I



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Technical Report 1584
March 1994

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ADMINISTRATIVE INFORMATION

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SUMMARY

REQUIREMENT

There is a continuous need for deep-submergence unmanned underwater vehicles (UUVs) in the search, salvage, exploration, and surveillance of the ocean floor. These vehicles require pressure-resistant housings, or complete pressure-resistant hulls to provide a dry, one-atmosphere environment to onboard equipment such as electronics and batteries. To maintain neutral buoyancy while submerged, the pressure-resistant hulls must be light enough to provide excess positive buoyancy that will compensate for the in-water weight of vehicle hardware. Maximum pressure hull buoyancy is achieved by fabricating the hulls with structural materials that have high values of specific compressive strength and specific elastic modulus (reference 7).

APPROACH

Of the available structural materials for pressure hull fabrication, ceramic materials possess the highest values of specific strength and modulus. A study of commercially available ceramic compositions reveals that 96-percent aluminum oxide ceramic (alumina) is currently the best candidate for the design of UUV pressure-resistant enclosures. Alumina has excellent structural properties, its raw material costs are low, and its fabrication technology has been adequately developed to allow manufacture of large cylindrical and hemispherical hull components with minimum risk. To demonstrate the capability of alumina ceramic for pressure hull applications, a 26-inch outer diameter (OD) by 91-inch-long cylindrical pressure housing assembly was designed for a service depth of 20,000 feet (9,000 psi), assembled, and subjected to a rigorous pressure-testing program. Testing of the 26-inch-OD housing was to include a proof test to an external pressure of 10,000 psi (1.1 times the design operating pressure) and 500 external pressure cycles to 9,000 psi.

RESULTS

All three major alumina ceramic subassemblies (the cylindrical hull and its forward and aft hemispherical end closures) survived proof tests to 10,000-psi external pressure. The alumina hemispherical end closures designed for the 26-inch-OD pressure housing also have demonstrated the capability to survive 500 external pressure cycles to design depth without catastrophic failure. Successful completion of such a high number of dive cycles ensures that large ceramic housings can be constructed which provide an adequate safety margin against failure by fatigue. The 26-inch-OD housing assembly has a dry weight of 876 pounds while displacing 1,496 pounds of seawater when submerged, resulting in a net lift of 620 pounds (weight/displacement=.585). This represents a three-fold increase in lift over a titanium rib-stiffened pressure housing designed to the same operational requirements (identical external dimensions and design depth).

CONTENTS

FIGURES

TABLE

INTRODUCTION

This report documents the fabrication, inspection, assembly, and pressure testing performed in support of a 26 inch outer diameter (OD) by 91-inch-long ceramic pressure housing designed at the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD). The 26-inch-OD housing is one of two large housings to be designed and tested by NRaD. The second pressure housing will be a 33-inch-OD by 113-inch-long assembly.

This is the fifth of six reports documenting NRaD's investigation into using alumina ceramic hulls for large external pressure housings on unmanned underwater vehicles (UUVs). Two of these reports explore metallic joint ring design and bonding techniques for ceramic external pressure housings (references 2 and 3). Documentation of the design and structural analysis performed for the 26-inch-OD and 33-inch-OD housings along with engineering drawings for each of the housing components is covered in a third report (reference 1). A fourth report presents findings of external pressure tests performed on a half-scale model of the 26-inch-OD housing (reference 16). The final report of this series covers results of pressure testing of the 33-inch-OD alumina-ceramic pressure housing assembly (reference 5).

The outstanding benefit of using ceramic materials like alumina in the construction of pressure-resistant hulls for UUVs lies in the low housing weight-to-displacement (W/D) ratios that can be obtained. A lower W/D ratio implies that the pressure housing will provide increased buoyancy to the vehicle assembly, allowing the system to be designed for optimal performance. Lower W/D ratios are achievable with ceramic materials because of their excellent specific compressive strengths and specific elastic modulus when compared to other hull material candidates such as titanium. The calculated W/D ratio of the 26-inch housing is 0.585, based on a dry structural weight of 876 pounds and a displacement in seawater of 1,496 pounds. Thus, the ceramic 26-inch housing provides a net lift of 620 pounds to a UUV system, which is approximately three times the lift obtained from an equivalent rib-stiffened titanium 26-inch housing designed to the same operational requirements (reference 1).

The 26-inch-OD housing represents part of the fifth generation of ceramic housings designed and tested at NRaD to demonstrate the feasibility of constructing pressure-resistant housings for deep-submergence applications with alumina ceramic as the primary structural material. Each generation of housings has evolved by fabricating progressively larger ceramic hull components (references 12 through 16). The 26-inch-OD and 33-inch-OD housings represent the largest ceramic underwater housings that have been assembled and pressure tested to date. Each housing is capable of acting as a dry one-atmosphere enclosure for batteries and electronics for UUVs with depth capabilities to 20,000 feet.

The objective of the development of the 26-inch-OD housing was to show that large alumina-ceramic housings will perform safely and reliably while exceeding the performance of traditional metallic enclosures. The following issues had to be addressed to demonstrate the feasibility of large ceramic external pressure housings:

- Fabricate large alumina hull components that possessed the structural integrity required for UUV pressure housings
- Qualify methods of assuring quality control of large alumina hull components using non-destructive evaluation (NDE) techniques
- Establish acceptability criteria for defects in alumina pressure hull components
- Incorporate design concepts from earlier-generation prototype housings into full-scale housings
- Develop procedures for assembling a large ceramic housing with adhesively bonded metallic joint rings

These issues, as well as the results of the pressure tests and post service inspection performed on the 26-inch-OD ceramic housing assembly are addressed in the various sections of this report.

FABRICATION

ALUMINA-CERAMIC COMPONENTS

The ceramic cylinders and hemispheres used as the main hull components of the 26-inch housings were fabricated by WESGO, Inc. of Belmont, CA, using their alumina-ceramic composition AL-600. AL-600 consists of 96-percent alumina (aluminum oxide) crystals with an average grain size of 8 microns. The remaining 4 percent of the ceramic body consists of additives that aid in bonding the aluminum oxide crystals together. These binders are primarily oxides of silicon, calcium, and magnesium. AL-600 was selected over other alumina compositions because it offered the best tradeoff between mechanical properties and the capacity to be economically fabricated into large hull shapes. Table 1[1] compares the properties of AL-600 with other alumina compositions available from WESGO. Figure 1 shows manufacturing methods that have been developed for fabricating parts from alumina ceramic. The path indicated by the dashed line outlines the steps used to fabricate the alumina components for the 26-inch housing.

The 26-inch housing consisted of two alumina cylinders for the cylindrical portion of the hull with alumina hemispherical bulkheads as aft and forward end closures. Both cylinders had a 25-inch OD, 0.90-inch-thick walls, and a 31.90-inch length (per drawing 55910-0127544 shown in figure 2). The Type 4 and Type 6 alumina hemispheres used as end closures also had 25-inch ODs at their equatorial skirts (per drawings 55910-0127649 and 55910-0127755 shown in figures 3 and 4). All four of these components were fabricated by isostatic pressing. The first step of this process is the alumina powder preparation where alumina particles, binders, and water are milled together to create a well-blended slurry. A spray dryer is used to atomize the slurry to create uniform, free-flowing powder agglomerates consisting of spherical particles of alumina and binders. This agglomerate is screened for the desired particle size, and the resulting material is referred to as processed alumina powder.

The next step in fabricating alumina hull components is to transform the processed alumina powder into a green body (green compact) by forming the powder into shapes using isostatic pressing. Isostatic pressing involves filling a mold (as shown in figure 5 for the 25-inch-OD cylinders) with processed alumina powder and applying uniform external pressure to the mold in a hydrostatic pressure chamber. The isostatic pressing mold has a lubricated internal steel mandrel and an outer flexible elastomeric bag (isobag) with accessory hardware for sealing and handling the mold during pressing. Figure 6 shows the mold with alumina powder encased as it is being lowered into a hydrostatic pressure chamber for isostatic pressing. The isostatic pressing was performed at the Arctic Submarine Laboratory (ASL) of the Naval Undersea Warfare Center Division, Keyport, WA. This ASL pressure chamber is routinely used by the industry for isostatic pressing of large ceramic components.

Once inside the chamber, the mold assembly is slowly pressurized to a maximum pressure of 10,000 psi, held for a period of 10 to 20 minutes, and then gradually decompressed. The isostatic pressing process was selected over other forming methods to compact alumina powder. Other methods such as slip casting and extrusion were inappropriate because of their size and thickness limitations. Additionally, the uniform compaction associated with isostatic pressing results in finished parts that have more reliable material properties than obtainable from these alternative forming techniques. After the isostatic pressing is completed, the mold is taken from the pressure chamber, the isobag is removed, and the green body is slid off the lubricated steel mandrel (figures 7 and 8). At this point, the green body is ready to be transported for green machining (fig-ure 9). Figure 10 shows the mold used to form 25-inch-OD hemispheres used for the 26-inch housing, while figure 11 shows a green body for a 25-inch-OD hemisphere after isostatic pressing has been completed. Both the forward and aft head hemisphere designs were fabricated using the same isostatic pressing mold.

[1]Figures and tables are placed at the end of the text.

Green machining is performed on each of the green bodies after pressing to remove excess material or to create design features that could not be introduced during the forming process. Material removal is more easily accomplished when the ceramic body is in the green state than after it has been fired. After each part is green machined, it is then ready to be fired (sintered) in a kiln. Sintering the green body results in consolidation of the ceramic body to achieve the physical and mechanical properties of the finished part. This consolidation process results in net shrinkage of the ceramic body by between 15 and 20 percent requiring special care in handling the ceramic component during firing to minimize distortion.

After the parts have been fired, machining to finished dimensions is performed by diamond grinding. A diamond grinding wheel is metallic with diamond grit embedded on its surface, with a soft metal or organic resin matrix. The parameters involved in diamond grinding such as infeed rate, wheel speed, coolant type, grit size, and concentration are critical to achieving the desired surface finish with a minimum amount of subsurface damage (reference 9). The following table lists the grinding procedures used by WESGO to finish the alumina components used in the 26-inch-housing assembly:

Item	Roughing Parameters	Finishing Parameters
Material Removal	to 1.0 inch	0.01 to 0.02 inch
Infeed Rate (in)	0.0005 - 0.001	0.0005 - 0.001
Wheel Surface Speed	4,000 fpm	4,000 fpm
Coolant	Water-base lubricant, sprayed, filtered	Water-base lubricant, sprayed, filtered
Wheel Type	metal bonded diamond	resin bonded diamond
Grit Size	100	180 - 320
Concentration (%)	75 - 100	75 -100

Wheels of 180 grit were used to finish grind all circumferential surfaces, while wheels of 320 grit were used to finish grind the axial bearing surfaces of each of the alumina hull components.

Each step of fabrication has risks. Manufacture of low quantities of unique ceramic parts, as used in the 26-inch housing, typically requires that extra parts be isostatically pressed to provide a safety margin against problems that may arise during fabrication. Four cylinders were pressed to yield the two finished parts required for the 26-inch-housing assembly. Similarly, eight hemispheres were isostatically pressed to yield the two hemispherical end closures needed.

Mechanical and physical properties for each of the delivered 26-inch-housing alumina-ceramic AL-600 components were generated through tests performed on material specimens taken from each part, or from specimens co-processed with each part, from the identical alumina powder lot. These tests were used to measure compressive elastic modulus, compressive strength, flexural strength, Weibull Modulus, and density. A summary of the average values for each of the parameters is presented below for the 25-inch-OD cylinders (part numbers 544-3 and 544-4) and the 25-inch-OD hemispheres (649-4 and 755-4). More detailed results of these tests are presented in appendix A.

Cylinder Part Number	**544-3**	**544-4**
compressive modulus	48.87 Mpsi	48.68 Mpsi
compressive strength	387.3 kpsi	412.9 kpsi
flexural strength	43.5 kpsi	43.6 kpsi
Weibull Modulus	29	28
density	0.136 lb/in^3	0.136 lb/in^3
Hemisphere Part Number	**649-4**	**755-4**
compressive modulus	45.41 Mpsi	48.26 Mpsi
compressive strength	409.3 kpsi	359.7 kpsi
flexural strength	50.3 kpsi	50.3 kpsi
Weibull Modulus	18	19
density	0.135 lb/in^3	0.136 lb/in^3

Compressive elastic modulus was determined using pulse-echo techniques on eight specimens for each part. Uniaxial compressive strength measurements were performed using ten 1/4-inch-diameter by 1/2-inch-long cylindrical specimens for each part. Flexural strength measurements were performed by subjecting twenty 2-inch-long by 1/4-inch-wide by 1/8-inch-deep chamfered specimens for each part to four-point bending. Weibull Modulus was based on flexural strength specimen data. The density of AL-600 ceramic was determined acoustically with the same eight specimens for each part used to determine the compressive modulus.

METALLIC COMPONENTS

In addition to the 96-percent alumina-ceramic hulls, the other primary structural components used in the assembly of the 26-inch housing were the titanium end-cap joint rings and the titanium central-stiffener joint ring used at the interface between adjacent ceramic sections. Engineering drawings of each of the three joint rings used in the 26-inch-housing assembly are shown in figures 12, 13, and 14. Figure 15 shows the titanium alloy Ti-6Al-4V rolled ring forgings from which the end caps and central stiffener for the 26-inch housing were machined. Typical values of 167,000 psi and 158,000 psi for the ultimate tensile strength and yield strength were reported for these forgings. Figure 16 shows a single rolled ring forging being rough machined into an end-cap joint ring for one of the 26-inch-housing alumina hemispherical end closures.

Prior to joint ring finish machining, fixtures were used to weld ears to the inner flange of each cylinder end-cap joint ring (figure 17). Electron beam welding was used where possible to minimize distortion in the finished rings. The ears provided a means of mounting internal hardware such as pre-tensioned tie rods and payload rails. Figure 18 shows a cylinder end-cap joint ring after final machining. Figure 19 shows the central stiffener used to join the two 25-inch-OD alumina cylinders together to construct the cylindrical hull portion of the 26-inch housing.

In order that each of the major subassemblies of the 26-inch housing (cylindrical hull section and two hemispherical end closures) could be proof tested separately, two steel alloy hemispheres were designed to be interchangeable with the alumina-ceramic hemispherical end closures. These hemispheres were fabricated from the 4340 steel alloy billets shown in figure 20. The hemispheres were rough machined prior to welding a lifting lug into place. After welding, each hemisphere was heat treated to achieve a minimum ultimate tensile strength of 180,000 psi and then was finished machined. A completed steel hemispherical end closure is shown in figure 21.

The Type 6 alumina-ceramic hemispherical end closure used as the forward head of the 26-inch housing contains six ports, each consisting of a through hole in the ceramic shell fitted with a titanium insert. Inserts for two of these ports contain military straight threads for pressure-relief valves. The penetrations for the remaining four ports contain 1.500-12UNF-2B threads for electrical connectors or electrical feed-throughs. The pressure-relief valve ports and electrical connector ports were achieved via assembly of the hardware as shown in figures 22 and 23. The bottom row of components in figure 22 shows the pressure-relief valve insert piece parts both individually and assembled together. The top row of figure 22 shows plugs that mate with the pressure-relief valve ports that were used during pressure testing. The bottom row of figure 23 shows the individual components used to provide the threaded ports for electrical connectors and feed-throughs in the forward head end closure. The top row of figure 23 shows the assembled insert piece parts together, along with both a plug and strain-gage-wire feed through that mate with the electrical connector insert assembly.

All titanium insert components were machined from Ti-6Al-4V alloy bar stock, while mating plugs and feed-throughs were machined from corrosion-resistant steel alloys (type 303 or type 17-4PH). The washer and spacer used to isolate the surfaces of the titanium insert from the alumina shell were machined from laminated sheets of cotton-fabric reinforced phenolic.

COMPOSITE COMPONENTS

In addition to using ceramic and metallic components to construct the 26-inch-housing assemblies, composite materials also were utilized to fabricate an external fairing to protect the ceramic hull components against impact and to fabricate bearing-surface gaskets to protect the ends of the ceramic hull sections. Figure 24 shows the fairing components used to protect both the cylindrical section and the forward and aft head end closures for the 26-inch-housing assembly. The fairing components were fabricated from a prepreg cloth woven with Spectra, an extended ultra-high molecular-weight polyethylene fiber developed by Allied Signal, Inc. Fabrication was performed by Advanced Composite Technologies of Sparks, Nevada via hand lay up of prepreg cloth (Spectra 1000PT/RS-1, fabric style 985) on a hard mold. The lay up for each part was then vacuum bagged and cured in an autoclave. Typical average mechanical properties for this material as determined from test specimens co-processed with the fairing components are as follows:

compressive strength:	8.1 kpsi
tensile strength:	60 kpsi
tensile modulus:	2.4 Mpsi
flexural strength:	21.3 kpsi
flexural modulus:	2.4 Mpsi

Annular gaskets machined from autoclave consolidated panels of graphite fiber-reinforced (GFR) poly-ether-ether-ketone (PEEK) matrix composite were to serve as gaskets for protection of the axial bearing surfaces of the 26-inch-housing alumina hull components. Each consolidated panel used to fabricate the bearing-surface gaskets consisted of eight plies (0/90) of prepreg cloth (APC-2/AS4 matrix and fiber) resulting in a 0.040-inch-thick part.

PRE-SERVICE QUALITY CONTROL OF ALUMINA-CERAMIC COMPONENTS

DIMENSIONAL INSPECTION

After fabrication of each of the 26-inch-OD housing alumina hull components, a rigorous inspection procedure was developed to ensure the quality. This inspection involved a complete comparison of each part against the dimensions and tolerances specified on the engineering drawing. In addition, both surface and volumetric inspection techniques were employed to detect flaws or defects that could affect the structural performance of the 26-inch-housing assembly.

The dimensional inspection data sheets for each of the 26-inch-housing alumina hull components are presented in appendix B. Of specific interest are the very tight dimensional tolerances and excellent surface finishes that can be achieved by diamond grinding. The range in tolerance for the outer diameter and wall thickness of each of the cylinders ranged around plus or minus 0.002 inch which exceeds the tolerances specified on the engineering drawing for these parts. Similar tolerances were obtained for the alumina hemispherical components used for the forward and aft head assemblies.

The surface finish called out on the engineering drawing for the axial bearing surfaces of the cylinders and hemispheres was specified as 16 microinches. Inspection of the dimensional data sheets for these parts reveals that the surface finish ranged from 5 to 14 microinches as measured with a diamond stylus indicator. In addition to the finish inspection of each component, a visual inspection using liquid dye penetrant was performed to inspect the surface for defects such as cracks, blister, holes, porous areas, or inclusions. The alumina-ceramic components also were visually inspected to ensure that the surface of each part was uniform in color and texture, and was free of any adherent foreign particles.

NONDESTRUCTIVE EVALUATION

In order to inspect each ceramic component for internal flaws, a rigorous NDE plan was developed using both ultrasonic and radiograph techniques. Witness standards were used for calibrating ultrasonic equipment in order to inspect the 26-inch-housing ceramic parts procured from WESGO. The engineering drawing used to fabricate these standards is shown in figure 25. Each standard is fabricated from the same 96-percent alumina

composition (AL-600) used for each of the ceramic hull components. Controlled flaws were introduced into these standards by placing pore-forming materials into the processed alumina powder prior to isostatic pressing. Pore-forming materials such as sugar, nylon, and polyethylene were selected that would pyrolize during sintering and leave an internal cavity of known size, shape, and location.

These witness standards were mounted in a fixture (figure 26) as shown in figure 27. This assembly then could be used for calibrating the ultrasonic equipment. A typical ultrasonic C-scan of a single witness standard is shown in figure 28 for calibration standard SK9402-093-C2 (0.030 pores scattered over approximately half the length of the standard). The original procedures for NDE of the 26-inch-housing alumina components were as follows:

1. Ultrasonic equipment shall be calibrated to detect the inclusions present in the 0.030-inch pore-calibration standard SK9402-093-C2 with a pulse-echo longitudinal wave C-scan. Scanning of the 0.030-inch pore-calibration standard shall be done at both a 0.010-inch and a 0.030-inch index. If the 0.030-inch index scan detects all 0.030-inch pores as indicated by the 0.010-inch index scan, then the 0.030-inch index shall be used for all subsequent inspections of the 26-inch-housing ceramic components. A pulse-echo longitudinal wave C-scan recording of the 0.030-inch pore-calibration standard with a description of equipment and settings used shall be provided with the final NDE report for each part. Using the settings and index determined above, a pulse-echo longitudinal wave C-scan inspection shall be performed on each of the 26-inch-housing ceramic components. A-scan recordings of all internal indications on the order of 0.030 inch or larger shall be provided. Any indications larger than 0.030 inch shall be reinspected using either the 0.050-inch pore-calibration standard SK9402-093-E2 or the 0.100-inch pore-calibration standard SK9402-093-F2 as required to determine the approximate size of the flaw. The locations of all indications on the order of 0.050 inch or larger shall be marked on the exterior surface of the ceramic part to aid all further NDE. Any indications determined to be on the order of 0.050 inch or larger shall be subsequently radiographed to further characterize the shape and location of the flaw. All radiograph film shall be included with A-scans and C-scans in the final NDE report for each ceramic part.
2. A +45 degree angle beam circumferential shear wave C-scan inspection shall be performed on each of the 26-inch-housing ceramic components based on the index and settings obtained from calibration with standard SK9402-093-C2. A shear wave C-scan recording of the calibration standard SK9402-093-C2 with equipment and settings used shall be provided with the final NDE report for each part. Any subsurface indication on the order of 0.050 inch or larger shall be radiographed. A –45 degree angle-beam circumferential shear wave C-scan shall be performed on the 26-inch-housing ceramic components. All new indications on the order of 0.050 inch or larger shall be radiographed. C-scans and radiographs, if required from both shear wave inspections, shall be included in the final NDE report for each part.

The intent of performing pulse-echo shear wave C-scans in addition to the pulse-echo longitudinal C-scan was to aid in detecting near-surface flaws that might be missed by the longitudinal scan. After inspection of the first 25-inch-OD ceramic cylinder (part 544-3) it was determined that the longitudinal C-scan was able to detect all internal flaws that existed, including the near-surface flaws that were present. In addition, it was decided that subsequent inspection of parts would be performed after each part had been rough finished only. This would eliminate investing time and resources in finish grinding a part that might later be rejected because of internal defects. Inspecting rough-ground parts eliminated the need for near-surface flaw detection via shear wave C-scans since the near surface was to be removed later in final grinding. Consequently, the second 25-inch-OD cylinder (part 544-4) and both 25-inch-OD ceramic hemispheres used for end

closures were ultrasonically inspected using a pulse-echo longitudinal C-scan only.

Ultrasonic inspection of the first 25-inch-OD alumina cylinder (part 544-3) detected the presence of 13 internal pores on the order of 0.030 inch or larger Three of these voids (UT-1, UT-3, UT-13) were approximately 0.050 inch in size. The depths of these three flaws varied as determined from A-scans generated for each flaw. UT-1 occurred at a depth of 0.130 inch from the part OD, UT-3 occurred at a depth of 0.750 inch from the part OD, and UT-13 occurred at a depth of 0.335 inch from the part OD. All of the ultrasonic inspections were performed at Sonic Testing and Engineering, Inc. of Southgate, California by immersing the ceramic components individually in a large water-filled tank.

Ultrasonic inspection of the second 25-inch-OD alumina cylinder (part 544-4) detected four internal voids on the order of 0.030 inch or larger. One of these defects (UT-4) appeared to be slightly larger than 0.050 inch and was located at a depth of 0.447 inch from the part OD.

Ultrasonic inspection of the Type 4 and Type 6 25-inch-OD hemispheres (parts 649-4 and 755-4) did not reveal any internal discontinuities greater than 0.030 inch, and, consequently, both parts were accepted for assembly without subjecting them to radiography. Radiographs taken of all indications on the order of 0.050 inch in size found in the two cylinders showed these flaws to be internal pores, and, as a result, both cylinders were accepted. The internal pores found most likely resulted from impurities that existed in the processed alumina powder prior to isostatic pressing of each part.

ASSEMBLY

CYLINDRICAL HULL SECTION

The cylindrical hull section consists of two 25-inch-OD alumina cylinder bays joined by a titanium central-stiffener joint ring. Remaining cylinder ends are encapsulated with titanium end-cap joint rings. Eight tie rods and two payload rails are mounted internally, and the exterior of the hull is covered with a composite fairing for impact protection. The assembly drawing of the 26-inch-housing cylindrical hull is shown in figure 29.

Various simple fixtures were designed to aid in the assembly of the 26-inch-housing cylindrical hull as shown in drawing SK9402-099 (figure 30). The fixtures and cradles are shown in figures 31 and 32. The assembly of the 26-inch-housing cylindrical section was performed in six steps.

The first step involved bonding GFR PEEK composite gaskets to the axial bearing surfaces of each alumina cylinder. Prior to bonding, the surfaces of the composite gasket and the bearing surfaces of the cylinder were cleaned with methyl ethyl ketone (MEK). A composite gasket was then centered on a cylinder end with the aid of the fixture SK9402-099-10 (figure 30). The interface between the gasket and the OD of the cylinder was sealed with five-minute epoxy and allowed to dry. Fixture SK9402-099-10 was removed, and the interface between the gasket and the ID of the cylinder was sealed with five-minute epoxy. This process was completed for both ends of each of the two alumina cylinders.

The second step involved bonding the central-stiffener joint ring to one end of the alumina cylinder used for the first bay. Figure 33 shows the first cylinder being lowered into the U-shaped epoxy-filled gland in the central-stiffener joint ring. The other end of the cylinder was protected during this step by a dry fit of one of the titanium end-cap joint rings. The U-shaped gland of the central stiffener was depassivated and cleaned with MEK before assembly. Exterior surfaces of the central stiffener then were coated with a layer of silicone-based mold release to aid in the cleanup of excess epoxy after bonding had been completed. A mixture of 100 parts CIBA GEIGY 6010 epoxy resin and 70 parts CIBA GEIGY 283 hardener was degassed in a vacuum chamber. The U-shaped gland in the central stiffener was partially filled with the epoxy mixture and centered on an aluminum base plate, SK9402-099-1 (figure 30), with the aid of a wooden center, SK9402-099-4 (figure 30).

Once the first bay cylinder had been lowered into the epoxy-filled gland of the central stiffener, an aluminum plate, SK9402-099-2 (figure 30), with

wooden center, SK9402-099-5 (figure 30), was placed on top of the cylinder. This subassembly was clamped together with four external tie rods, SK9402-099-8 (figure 30), as shown in figure 34. The clamping force applied to the fixtures assured that the assembled cylinder was completely aligned and seated in the central-stiffener joint ring gland. Excess epoxy that extruded from the joint ring during this step can be seen in figure 34. This excess epoxy was easily cleaned from the exterior surfaces of the joint ring once the epoxy had partially cured over a period of 24 hours. After the epoxy had fully cured, a bead of room-temperature vulcanizing (RTV) sealant was applied to the edges of the central stiffener to prevent water intrusion into the cylinder/joint-ring bond during pressure testing.

The third step involved bonding a titanium end-cap joint ring to the remaining end of the alumina cylinder used for the first bay. Depassivation and cleaning of the internal surfaces of the end-cap joint ring and the application of mold release to external surfaces of the end-cap joint ring proceeded as performed for the central stiffener in the second step of the assembly process. The key for the third step was to maintain correct alignment of the end cap with the central stiffener for eventual assembly of internal components (tie rods and payload rails). Figure 35 shows the first bay of the cylindrical hull section after completion of the second and third steps of the assembly process.

The fourth step required bonding a titanium end-cap joint ring to the cylinder used for the second bay. Preparation of the joint surfaces and the assembly technique for this joint ring paralleled the steps described above for bonding joint rings to the first cylinder.

The fifth step involved joining the two bays of the cylindrical hull section together by bonding the second cylinder to the central-stiffener joint ring (figures 36 through 38). The first bay assembly was covered externally and internally with plastic sheeting to simplify cleanup of excess epoxy. The critical part of this step was alignment of the internal mounting points on the second cylinder end cap with the mating hole patterns on the central stiffener and end cap previously bonded to the first cylinder. Longer tie rods, SK9402-099-9 (figure 30), were used to aid seating and alignment during this step. Figure 39 shows the cylindrical hull section after completion of epoxy bonding of the hull's major structural components.

The cylindrical hull was set on cradles with the handling fixture as shown in figure 40. In this position, the sixth and final assembly step for the hull section, the attachment of internal tie rods and rails and external fairing, was completed (figures 41 and 42). Figure 43 shows an internal view of the completed hull section with four tie rods per bay and two payload rails running the length of the interior. To facilitate shipping of the cylindrical hull section of the 26-inch housing, the payload rails were removed (figure 44) and the hull was packaged (figure 45) for delivery to the pressure testing facility at Southwest Research Institute (SRI), San Antonio, Texas.

HEMISPHERICAL END CLOSURE SECTIONS

The assembly drawing for the 26-inch-housing aft head end closure is shown in figure 46. The aft head consists of a Type 4 alumina hemisphere with an epoxy-bonded titanium end-cap joint ring and a protective composite external fairing. The 26-inch-housing forward head end-closure assembly drawing is shown in figure 47. The forward head is a Type 6 alumina hemisphere with six ports, a titanium end-cap joint ring, and an external composite fairing. The fairing for each head is retained in place with a split V-band clamp also fabricated from composite materials. Bonding the titanium end-cap joint rings to each alumina hemisphere was performed with the fixtures shown in figure 48 and a hydraulic lift truck.

During the time between the fabrication of the alumina cylinders and the hemispheres for the 26-inch housing, a parallel study focused on the cyclic fatigue life of alumina cylinders assembled with metallic joint rings using various bonding techniques (reference 3). Several assembly methods that incorporate an inter-layer of a gasket material as an axial bearing support between the alumina hull and the metallic joint ring were evaluated. Two of the methods compared were: the use of a thin intermediate layer of epoxy between the bearing

surfaces of the joint ring and the ceramic hull, and the use of a GFR PEEK gasket placed adjacent to the bearing surfaces of the ceramic component as used with the 26-inch-housing cylindrical hull assembly described above. GFR PEEK gaskets had been used previously in the assembly of the half-scale model of the 26-inch housing with good results (reference 16).

In this study, the alumina 12-inch-OD cylinders assembled with these two different axial bearing surface supports were pressure cycled, disassembled, and nondestructively evaluated to determine the extent of subcritical crack growth that had occurred in the axial bearing surface region of the cylinder ends during testing. It was concluded that a thin intermediate layer of epoxy performed at least as well as the GFR PEEK gaskets in terms of minimizing subcritical crack growth. In addition, the epoxy gasket had the benefit of lower cost and easier assembly. Several methods of ensuring the minimum thickness of the inter-layer of epoxy between the bearing surfaces of the joint ring and the ceramic hull were investigated during this study using various spacer techniques. An annular paper gasket used as a spacer was found to be an adequate approach and was selected for use in the assembly of the aft and forward heads for the 26-inch-housing assembly. The cyclic fatigue life of AL-600 12-inch-OD cylinders assembled with titanium end-cap joint rings and annular paper gaskets was investigated in a second parallel study (reference 4). It was confirmed that this assembly approach provided a cyclic fatigue life well in excess of 1,000 dive cycles at the stress levels at which the 26-inch housing was designed to operate.

The annular paper gasket used in epoxy bonding the titanium end-cap joint ring to the aft head of the 26-inch housing is shown in figures 49 and 50. Figures 51 and 52 show the Type 4 alumina hemisphere used for the aft head assembly. Preparation of the bonding surfaces of the titanium joint ring and the alumina hemisphere proceeded as described for the cylindrical hull assembly. In order to bond the end-cap joint ring to the alumina hemisphere, the joint ring was first centered on the table SK9402-090-1 (figure 48). In this position, the U-shaped gland of the joint ring was partially filled with the epoxy mixture, and the axial bearing surface paper gasket was placed in the joint ring as shown in figure 53 and pushed down through the epoxy mixture to the bearing surface at the bottom of the joint-ring gland. A wooden pedestal SK9402-090-2 (figure 48) was elevated above the table with the forks of a hydraulic lift truck so the alumina hemisphere could be centered above the epoxy-filled end-cap joint ring as shown in figure 54. Then, with the aid of the hydraulic lift truck, the hemisphere was lowered into the end-cap joint ring, clamped in place with tie rods (figure 55), and the epoxy was allowed to cure.

The aft head assembly for the 26-inch housing is shown in figure 56 without its protective external fairing and again in figure 57 with the fairing in place. The identical procedures used for the aft head assembly were used for the forward head. The completed forward head assembly is shown in figures 58 through 60. Only two of the six through holes intended for the forward head were finish ground prior to assembly. Postponing machining of the remaining four holes was done to expedite delivery of the alumina hemisphere so that pressure testing for the 26-inch housing could be completed on schedule.

The original design of the titanium inserts used in the through-hole ports of the forward head assembly are shown in figures 61 and 62. These inserts were dimensioned to have a nominal radial clearance of 0.002 of an inch when assembled to the Type 6 alumina hemisphere (figure 4). A tight tolerance fit was required to prevent extrusion of the insert O-ring into the radial clearance during external pressure loading. A dimensional inspection of the through holes in the forward head (appendix B) indicated that the holes were slightly oval. Therefore, it was decided to modify the inserts to increase the radial clearance in order to prevent uneven loading on the walls of the through hole. This change required that the fabric-reinforced phenolic spacers used between the alumina hemisphere and the inserts be redesigned to move the O-ring away from the shaft of the insert as shown in figures 63 and 64.

TEST PLAN

The test plan for the 26-inch-housing assembly was to individually proof test each of the three major subassemblies (cylindrical hull section, forward head hemispherical end closure, and aft head hemispherical end closure) to an external pressure of 10,000 psi. The rate of pressurization during each proof test was specified not to exceed 1,000 psi per minute followed by a 60-minute hold at a sustained pressure of 10,000 psi. The depressurization rate was not to exceed 10,000 psi per minute.

Biaxial electric resistance strain-gage rosettes were to be mounted at specific internal surface locations on each subassembly, waterproofed, and read at 1,000-psi intervals to 10,000 psi during the proof test. In addition, the strains were recorded for the cylindrical hull assembly at 200-psi increments between 9,000 and 10,000 psi. Additional strain measurements were made for the cylindrical hull near the proof pressure to identify nonlinear deformations that could occur should buckling of the hull assembly be incipient. Ninety-degree rectangular rosette strain gages were used with one leg oriented in the hoop direction and the other in the meridional direction. Strain gages were placed at midbay of the cylindrical hull on the titanium central stiffener since any deformations associated with general instability would be most pronounced at this location. Strain gages were to be read following the 60-minute hold at 10,000 psi and read again for any residual strains after depressurization to 0 psi.

Acoustic emissions data were to be recorded throughout the proof test of the cylindrical hull assembly. Acoustic emissions data were tracked via a transducer bonded to the exterior of the pressure vessel. After completion of the proof test, each major subassembly was to be individually cycled a minimum of ten times to 9,000 psi external pressure with a one-minute hold at 9,000 psi during each cycle. Acoustic emissions data were to be recorded for the cylindrical hull assembly throughout the ten cycles to 9,000 psi.

The test assembly used to proof test the cylindrical hull section (figure 29) of the 26-inch housing is shown in figure 65. Ten strain gages were mounted to the interior surface of the central stiffened joint ring in the locations indicated. All testing fixtures designed for the proof test are shown in figures 66 through 72. The steel hemispheres in figure 66 were used as end closures to proof test the cylindrical hull section. A single lifting lug (figure 67) was welded in line with the center of gravity of each steel hemisphere to aid in assembling the hull section test assembly. An O-ring (figure 68) was used for a face seal between the cylinder end-cap joint ring at each end of the cylindrical hull section and the mating steel hemisphere. The aluminum-alloy clamp bands shown in figure 69 maintained closure between the hull section and the steel hemispherical end closures. Strain-gage leads and a vent line were passed from the interior of the test assembly by potting the feed through shown in figure 70 with two-part epoxy and urethane. The polar penetration in the remaining steel hemispherical end closure was capped with the –2 plug shown in figure 71.

The entire cylindrical hull section test assembly was mounted in the test fixture cage (figure 72). The 30-inch bore and 111-inch internal length of the pressure vessel dictated the design of the test fixture cage. The test fixture had eight belly bands clamping two aluminum channels to the external fairing of the 26-inch hull section. Shackle pad eyes were welded to one end of each channel while a pivot foot was bolted to the opposite end of each channel. Since the hull section was assembled horizontally (figure 73), the pivot foot allowed the hull test assembly to be lifted by the pad eyes into a vertical position (figure 74) and then lowered into the pressure vessel for testing (figure 75).

Prior to being used to proof test any of the major ceramic subassemblies of the 26-inch housing, the steel hemispherical end closures were proof tested together to an external pressure of 10,000 psi as shown in figure 76. Proof testing the two steel hemispheres together was performed to check all seals for leaks and to verify the structural integrity of the steel hemispherical end closures. Additional

testing components that were designed for proofing the steel hemispheres are shown in figures 77 through 79.

Individual proof testing of the forward head and aft head hemispherical end closures was performed as shown in figure 80 reusing many of the testing components described earlier. An additional plug (figure 81) was used to cap the pressure relief valves in the forward head hemispherical end closure. Proof tests of each of the alumina-ceramic hemispherical end closures was performed with the number and locations of strain gages as shown in figure 80. Figure 82 shows the test configuration for the aft head assembly as it is being lowered in the pressure vessel for proof testing to 10,000 psi. Figure 83 shows the test configuration for the forward head assembly prior to pressure testing.

TEST RESULTS

CYLINDRICAL HULL SECTION

All pressure testing work performed on the 26-inch housing assembly took place at SRI. The strains recorded from the interior surface of the central stiffener surface during the proof test of the cylindrical hull assembly are shown graphically in figures 84 and 85. These plots indicate that the recorded strains are increasing in a linear fashion throughout the pressurization to 10,000 psi. The average strains at 10,000-psi external pressure were –1,950 microinches/inch in the hoop direction and +2,580 microinches/inch in the axial direction. Two of the twenty channels used to record the strain gage data failed before reaching the 10,000-psi proof pressure. The slight variation in strains that were recorded from each gage is due to the fact that each rosette was bonded in place by hand. Variations in location and orientation of each gage would effect the magnitude of the recorded strains.

The total number of acoustic events emitted by the cylindrical hull section during the initial proof pressurization for 0 to 10,000 psi was 594 events. After attainment of 10,000-psi external pressure, the pressure was held for 60 minutes, during which time the cumulative total of acoustic events increased from 594 to 610. During the depressurization from 10,000 psi to 0 psi, the total number of acoustic events increased from 610 to 619. The depressurization took place at an average rate of 434 psi/minute.

Immediately after depressurization to 0 psi, pressure cycling to an external pressure of 9,000 psi for a total of ten cycles was initiated. Each pressure cycle consisted of pressurization to 9,000 psi at an average rate of 1500 psi/minute, followed by depressurization to 50 psi at an average rate of 5,000 psi/minute. The total number of acoustic emissions generated by the first nine pressure cycles was 27 events, indicating that during that period no cracks were initiated or propagating in the ceramic cylinders.

During performance of the tenth cycle, a mishap occurred. At the instant the pressure reached 9,000 psi, the 0.50-inch ID bulkhead penetration used for strain gage instrumentation leads through the vessel end closure failed catastrophically, resulting in a violent release of the pressure from inside the vessel chamber. The pen on the strip chart recording the number of acoustic emission events was pegged at its maximum position (400 events) during the rupture. The digital recorder used to count the number of acoustic emission events was drenched with water released through the bulkhead penetration after it failed, and, consequently, the exact number of acoustic emission events was not recorded.

The bulkhead penetration consisted of a tapped steel fitting with a 0.50-inch diameter bore, through which the strain gage leads and a vent line were fed. The remaining volume of the 0.50-inch bore was potted with a two-part epoxy by the technical staff at SRI, allowed to dry, and sealed with polyurethane. During the tenth pressure cycle, the bond between the potting material and the penetration bore failed, jettisoning the strain-gage leads and potting material into the rafters of the pressure testing laboratory, resulting in an instantaneous decompression of the 26-inch-housing cylindrical hull section.

The magnitude of the forces exerted on the cylindrical hull section were accentuated by the fact

that the hull test assembly occupied the bulk of the water volume in the pressure vessel. The loads acting on the hull section during this violent decompression are analogous to dynamic oscillatory forces felt by a spring as it is released from a compressed state. This unspringing of the vessel undoubtedly resulted in substantial tensile loading on the alumina cylinders. These tensile forces were accentuated by the inertia of the steel end closures moving in opposite directions from each other as the axial compression of the cylindrical hull assembly was suddenly released.

Following the explosive depressurization of the pressure vessel interior, the 26-inch-housing cylindrical hull test assembly was removed for visual inspection. The hull assembly appeared to be intact even though it appeared to jump within the test fixture cage, loosening the bolts that tighten the belly bands around the housing's external fairing. After tightening the belly bands, the housing assembly was lowered back into the pressure vessel for reapplication of a proof test to 10,000 psi.

This second proof test was to determine whether the structural integrity of the 26-inch-housing cylindrical hull section was compromised by the dynamic loading to which it was subjected during sudden depressurization. If the housing withstood the pressure test to 10,000 psi without significant acoustic activity it would be considered as proof that cracks were not introduced into the ceramic components of the housing structure during the catastrophic decompression event. If it passed this proof test, the housing could be mated with ceramic hemispherical end closures for further testing without fear of premature failure of the ceramic cylindrical hull section. On the other hand, if the pressure housing generated excessive acoustic events, or if it failed prior to reaching 10,000 psi, it would be considered damaged and would not be acceptable for further testing.

After zeroing out the acoustic events recorded during the catastrophic failure of the pressure vessel penetration, pressurization was initiated with the electric drive piston pump. Pressurization proceeded at approximately 2,000 psi/minute while acoustic events were continuously recorded. Little acoustic activity occurred until the pressure increased beyond 2,000 psi. In the interval between 2,000 psi and 3,000 psi, a momentary burst of acoustic activity produced 120 acoustic events. Thereafter, the acoustic activity settled down to a steady pace of approximately 8 events/1,000-psi pressure rise. When the pressure reached 9,000 psi, there was another sudden burst of acoustic activity generating an additional 230 acoustic events. The rate of acoustic emission increased as the pressure rose above 9,000 psi. Upon reaching 9,250 psi, catastrophic failure of the 26-inch-housing cylindrical hull section took place. Figure 86 shows the total number of acoustic emission events that were recorded for each pressure test performed on the 26-inch-housing cylindrical hull section. Figure 87 shows the cumulative number of acoustic emission events generated by the housing throughout all the pressure testing that was performed.

Inspection of the imploded cylindrical hull assembly did not detect any out of roundness in the joint rings, which indicates that the failure was not caused by buckling. The internal flange of one of the cylinder end-cap joint rings was pushed inward *at a single circumferential location*, as was the internal flange on one side of the central-stiffener joint ring. The flanges on the opposite side of the central stiffener and for the remaining end-cap joint ring showed no sign of permanent deformation. It appeared that one of the alumina cylinder bays imploded, resulting in failure of the entire cylindrical hull section. The high number of acoustic events recorded during the attempt to proof test the housing again after the explosive decompression indicates that cracks were propagating in at least one of the alumina cylinders. At least one of these cracks propagated to the point that it became critical enough to result in catastrophic failure of the entire cylindrical hull test assembly.

The difference in acoustic emission data prior to, and after, the sudden decompression mishap indicates that although the housing survived the pressure vessel accident in one piece, substantial cracks were introduced during the accident which resulted in hull failure during the subsequent repressurization test. Although the original proof test demonstrated the design of the cylindrical hull assembly would not fail by buckling at design

depth, extensive cyclic fatigue-life data to design-depth pressures were not obtained for the 25-inch-OD cylinders because of failure of the pressure-vessel bulkhead penetration during the tenth pressure cycle.

HEMISPHERICAL END CLOSURE SECTIONS

Loss of the cylindrical hull section changed the pressure test plan for the two remaining major subassemblies of the 26-inch housing. In addition to performing a 10,000-psi proof test with the forward and aft head hemispherical end closures mated to a steel hemispherical end closure, it was decided to cycle each head separately 500 times to an external pressure of 9,000 psi. Performing the cyclic tests of the forward and aft head end closures individually would provide more cyclic fatigue data for large 96-percent alumina-ceramic components than if the forward and aft heads were pressure cycled together.

Figure 88 shows the hoop strains recorded from the five gages bonded to the interior surface of the alumina hemisphere used for the aft head assembly during its proof test to 10,000 psi. As shown in figure 80, sheet 3, these gages were equally spaced along the meridian from the equatorial joint ring interface to the hemispherical pole. Since the wall thickness tapered along the meridian, the strains varied with gage location, with the highest strains recorded from rosette 20 (located at the pole where the minimum wall thickness occurs). As expected, all recorded strains increase in direct proportion to the applied external pressure.

The meridional strains recorded during the proof test of the Type 4 hemisphere used in the aft head assembly are shown in figure 89. The highest measured meridional strains occurred at rosette 16 due to bending caused by the geometric transition between the cylindrical equatorial skirt and the hemispherical shell wall.

After its proof test, the Type 4 alumina hemisphere used in the aft head assembly was subjected to 500 cycles to a peak external pressure of 9,000 psi. At 100 cycle intervals, the hemispherical assembly was removed from the pressure vessel, and the Type 4 hemisphere was inspected as shown in figure 90 to detect the presence of any fatigue cracking that may have developed during testing. No cracks were found, and the aft head assembly successfully completed all 500 pressure cycles.

The Type 6 alumina hemisphere used for the forward head assembly also surpassed a proof test to 10,000 psi and 500 cycles to the 9,000-psi design pressure. The hoop and meridional strains that were measured from the five gages bonded to the interior surface of the alumina hemisphere during the proof test are shown in figures 91 and 92. No hoop strain measurements were obtained from rosette 12 due to gage failure. The strains recorded from rosettes 13, 14, and 15 were identical, as expected, since they were located in the portion of the hemisphere with constant wall thickness. Hoop strains recorded from rosette 11 were lower because of their placement in the thicker transition region adjacent to the cylindrical equatorial skirt.

In addition to the forward and aft head assemblies, a third alumina hemisphere was received from WESGO that was assembled and subjected to a proof test to 10,000 psi and 500 cycles to 9,000 psi. This third part was intended to be a Type 4 hemisphere (tapered wall thickness without any holes) used in the aft head assembly, but was originally rejected because it did not meet the dimensional tolerances on engineering drawing 55910–0127649 (figure 3). It met the tolerances for the cylindrical equatorial skirt shown, but the wall thickness of the remainder (transition region from the skirt to the tapered hemispherical section) was approximately 0.040 inch undersized. Figure 93 shows wall thickness measurements being made with a hand-held ultrasonic thickness detector of the dimensionally disqualified Type 4 alumina hemisphere. One of the titanium end-cap joint rings used with the cylindrical hull assembly was refurbished and attached to this additional alumina hemisphere. Figure 94 shows this third hemisphere assembled with the dimensionally qualified aft head alumina hemisphere. This back-to-back alumina hemisphere configuration was not pressure tested, but, rather, the reject aft head

hemisphere was pressure tested with a steel test hemisphere.

Five strain gage rosettes were bonded to the interior of the reject aft head hemisphere in the same locations specified for the dimensionally qualified aft head hemisphere per figure 80. The strains recorded for this third hemisphere during its proof test to 10,000 psi are shown in figures 95 and 96. Because of its reduced wall thickness, the strains are higher than those recorded for the dimensionally qualified aft head hemisphere as presented in figures 88 and 89. Specifically, the hoop strain at the pole of the reject hemisphere was measured to be –2,963 microinches/inch at 10,000-psi external pressure as compared to –2,463 microinches/inch recorded for the aft hemisphere that met dimensional specifications. As with the first two alumina hemispheres tested, the reject aft head hemisphere also survived 500 cycles to 9,000-psi external pressure.

POST-SERVICE INSPECTION OF ALUMINA-CERAMIC COMPONENTS

After completion of the pressure testing program, the outer flange of the end-cap joint ring was removed from both the aft head end closure that used the dimensionally qualified Type 4 alumina hemisphere and the aft head end closure that used the dimensionally disqualified Type 4 alumina hemisphere. A horizontal lathe was used to remove the outer flange as shown in figure 97. Machining off the outer flange allowed for a full-immersion pulse-echo ultrasonic inspection of the bearing-surface region of each hemisphere to determine if any structural damage had occurred as a result of pressure testing.

Inspection of the dimensionally qualified Type 4 alumina hemisphere revealed that a circumferential crack had developed on the plain-bearing surface of the ceramic hemisphere in a single location. This crack was located at a depth of 0.25 inch from the OD of the equatorial skirt, had a circumferential length of 0.74 inch, and extended to a depth of 0.10 inch from the bearing-surface region. This crack appeared to be typical of previously observed bearing-surface cracks that formed in ceramic housing assemblies as a result of cyclic external pressure loading (references 4, 5, and 16). The very small amount of cracking found in the dimensionally qualified Type 4 alumina hemisphere indicates that this unit would have a cyclic fatigue life of well beyond the 500 pressure cycles to 9,000-psi external pressure to which it was subjected.

The dimensionally disqualified Type 4 alumina hemisphere assembled with the refurbished end-cap joint ring was found to have substantially more internal cracks in its bearing-surface region after completion of the 500 pressure cycles to 9,000 psi to which it was also tested. A pulse-echo C-scan generated of the entire cylindrical skirt region indicated that bearing-surface cracks had developed around the entire circumference of the hemisphere. These cracks had propagated to a minimum depth of 0.60 inch from the bearing surface and had grown as far as the transition region (2.50 inches) from the cylindrical skirt into the hemispherical shell in three locations.

Cracks that have propagated past the region of the ceramic shell encapsulated by the flanges of the joint ring can lead to eventual failure of the hull assembly. Delaminations caused by internal circumferential cracking can buckle under external pressure loading, resulting in spalling of ceramic shards from the surface of the ceramic shell wall. With spalling of the ceramic comes a loss of load-bearing material and potential leakage of water into the epoxy bond at the joint interfaces. In the case of the dimensionally disqualified Type 4 alumina hemisphere, the cracks extended into the shell wall beyond the two-inch-long flanges of the refurbished cylinder end-cap joint ring (figure 13). Thus, the fatigue life of this unit is not likely to be much greater than the 500 pressure cycles to 9,000 psi that it has already survived.

STRUCTURAL ANALYSIS

Structural analysis for the completely assembled 26-inch housing was presented in reference 1. Since all the testing that was performed for the 26-inch housings occurred with the three major hull assemblies pressurized individually, additional finite element analysis (FEA) of these three test

configurations is presented here. Finite element models (FEM) were generated by mating the ceramic cylindrical hull with steel test hemispheres at each end and joining the forward and aft head ceramic end closures with steel test hemispheres.

A cross section of the FEM used to calculate the stresses in the ceramic cylinders and the Type 4 ceramic hemisphere used in the aft head assembly are shown in figures 98 and 99. These figures show axisymmetric models constructed using the FEA software ANSYS-PC, revision 4.4A, a product of Swanson Analysis Systems, Inc. A symmetry point at midbay (at the axial centerline of the central-stiffener joint ring) was also used in the model of the cylindrical hull assembly (figure 98). All test assembly components were modeled using STIF82 2-D, eight-node quadrilateral solid elements with the following linear elastic isotropic material properties:

AL-600 96-percent alumina ceramic:
E=48.7 Mpsi (alumina cylinder)

E=45.4 Mpsi (Type 4 alumina hemisphere)

E=48.3 Mpsi (Type 6 alumina hemisphere)
v=.23

Titanium alloy Ti-6Al-4V:
E=16.4 Mpsi
v=.31

Epoxy:
E=300 kpsi
v=.40

Steel alloy 4340:
E=29 Mpsi
v=.32

Aluminum alloy 7075:
E=10.3 Mpsi
v=.33

where E is the elastic modulus and v is the Poisson's Ratio of each material.

STIF12 2-D gap elements were used to model the joint interfaces; for example, between the aluminum spacer ring and the steel test hemisphere, and between the aluminum spacer ring and the titanium end-cap joint ring that is epoxy bonded to the alumina hemisphere for the aft and forward head end closures. STIF12 elements are capable of supporting only compressive loads normal to the contact surfaces. These elements allow adjacent surfaces to maintain, or break, physical contact and allow one surface to slide relative to the other surface. The use of gap elements introduces nonlinearities into the stress analysis and, therefore, requires that an iterative solution be used when running the FEM.

FEM for each of three test assemblies were run using the maximum external pressure used during the cyclic testing of 9,000 psi. Figure 100 is a stress contour plot of the minimum principal stresses that exist in the ceramic cylinders at 9,000-psi external pressure. A peak compressive stress of -130,539 is calculated to exist at midbay of each ceramic cylinder and is oriented in the hoop direction. Figure 100 reveals that more bending is occurring at the ceramic cylinder interface with the central stiffener (as seen at the bottom of the figure) than at the cylinder interface with the steel test hemisphere. This implies that more radial support of the ceramic cylinder is given by the integrally bonded central stiffener than is provided by the steel test hemisphere. Figure 101 is a stress contour plot of the maximum principal stresses in the ceramic cylinder in the bearing-surface region adjacent to the cylinder end-cap joint ring interface with the steel test hemisphere for an external pressure load of 9,000 psi. A maximum tensile stress of +4,571 psi is predicted to occur at the plain axial bearing surface and is oriented in the radial direction.

Figure 102 is a contour plot of the minimum principal stresses that exist in the Type 4 ceramic hemisphere of the aft head end closure at 9,000-psi external pressure. A peak compressive stress of −154,187 psi is calculated to exist at the pole of the hemisphere. Figure 103 is a detailed view of the maximum principal-stress contour plot for the Type 4 hemisphere in the region of its equatorial bearing surface. This plot indicates that a maximum tensile stress of +7,434 psi occurs in the ceramic adjacent to the epoxy layer that separates the hemisphere axial bearing surface from the axial bearing surface of the titanium end-cap joint ring.

The results of the stress calculation from the FEM for the Type 6 hemisphere used in the forward head end closure are shown in figures 104 and 105. Figure 104 indicates that a peak compressive

stress of −199,941 psi occurs at a through hole located at the hemispherical pole (a 1.004-inch-diameter hole for a pressure-relief valve insert was used in the model) when the assembly is pressurized to 9,000 psi. The polar location of the through hole does not represent an actual location of one of the six holes that exists in the forward head. The polar location was used because it can be represented with an axisymmetric analysis and because the stresses around the hole will not vary with the location of the hole, as long as the holes are properly spaced and located in the portion of the hemisphere which has a constant wall thickness. The maximum tensile stress of +8,044 psi at the bearing surface of the Type 6 hemisphere shown in figure 105 is slightly higher than that calculated to exist in the Type 4 hemisphere at the same load level. This difference can be attributed to the differences in the elastic modulus used to model each hemisphere.

FINDINGS

1. The fabrication technology for isostatically pressed AL-600 alumina cylinders and hemispheres is sufficiently mature to allow manufacture of the hull components used in the 26-inch housing with minimum risk.
2. The following range of average material properties were found for the AL-600 alumina cylinders and hemispheres used in the 26-inch-OD pressure housing assembly:

compressive modulus	45.4 – 48.9 Mpsi
compressive strength	360 – 412 kpsi
flexural strength	43.5 – 50.3 kpsi
Weibull Modulus	18 – 29
density	0.135 – 0.136 lb/in^3

3. Economical and reliable quality control of the AL-600 alumina hull components for the 26-inch housing was performed using commercially available full-immersion pulse-echo ultrasonic inspection techniques. This inspection method was capable of detecting internal discontinuities as small as 0.015 inch in the ceramic shell wall. The largest defects found in any of the 26-inch-housing alumina components were internal voids approximately 0.050 inch in size.
4. Assembly of the 26-inch-OD by 91-inch-long ceramic-housing assembly was performed without difficulty using simple handling fixtures to epoxy bond titanium joint rings to the ends of each alumina hull section.
5. The design of the central-stiffening joint ring used to bond the two alumina cylinders in the cylindrical hull assembly of the 26-inch-OD housing was validated through a proof test to 10,000-psi external pressure (1.1 times the design depth). The cylindrical hull of the 26-inch-OD housing assembly was designed (reference 1) to have a minimum safety factor (SF) of 1.5 against buckling at its 9,000-psi design depth when capped by hemispherical end closures. The integral T-shaped ring of the central stiffening joint ring was sized to provide this 1.5 SF to prevent collapse by general instability at pressures below 13,500 psi.
6. The dimensionally qualified aft and forward head alumina hemispherical end closures of the 26-inch-OD alumina-ceramic housing assembly were found to have a cyclic fatigue life in excess of 500 cycles to an external pressure of 9,000 psi, generating the following peak stresses during each cycle:

   min. principal membrane stress: −154,187 psi

   min. principal stress at localized stress concentrator: −199,941 psi

   max. principal stress at localized stress concentrator: +8,044 psi

   The minimum principal membrane stress occurred at the pole of the Type 4 hemisphere used for the aft head end closure. The minimum principal stress at a localized stress concentrator was found at the through holes of the Type 6 hemisphere used for the forward head end closure. The maximum principal stress at a localized stress concentrator occurred at the plain axial-bearing surface of the Type 6 hemisphere at its bond interface with its end-cap joint ring.

7. The dimensionally disqualified Type 4 alumina hemisphere was found to have a fatigue life of 500 cycles to an external pressure of 9,000 psi. The wall thickness of this reject part was 0.040 of an inch undersized everywhere, except at its cylindrical skirt. This reduced wall thickness resulted in compressive membrane stresses that were approximately 11-percent greater in magnitude (–172 kpsi at the pole) than those that existed in the dimensionally qualified Type 4 alumina hemisphere.

8. The pressure testing program completed by the forward and aft heads validates the equatorial cylindrical skirt at the bearing surface of the ceramic end closures as a worthy design feature for improving cyclic fatigue life of hemispherical end bells. Successful completion of proof and cyclic testing by the forward head end closure also demonstrates that ports for electrical connectors, pressure-relief valves, etc., can be successfully made using metallic inserts in the ceramic shell wall. The titanium insert penetrators designed for the forward head end closure did not serve as crack initiators in the ceramic hemisphere during pressure cycling.

9. As with the ceramic pressure hulls tested in earlier generations of NOSC[2] and NRaD housings, the cyclic fatigue life of the alumina hull sections of the 26-inch-OD housing assembly is determined by the initiation and propagation of cracks that originate on the bearing surface of ceramic component ends at their interface with metallic joint rings.

DISCUSSION

1. The intent in performing ultrasonic and radiographic inspection of the ceramic hull components of the 26-inch housing was to ensure that no gross fabrication defects were present that could compromise the structural integrity of the pressure housing assembly. The acceptance of the 26-inch housing's ceramic components with 0.050-inch pores is based on NRaD's quality control experience with engineering ceramics and is not based on a critical flaw size in the performance of alumina pressure hulls. NRaD has never documented the failure of a ceramic pressure hull due to the presence of a defect that was identified in pre-service inspection. Rather, cyclic fatigue is thought to initiate at stress concentrations around micro pores located near the bearing surfaces at ceramic component ends (reference 9). This intrinsic microporosity is a characteristic of AL-600 alumina and can not be detected using the NDE techniques described in this report.

2. Although both the dimensionally qualified and dimensionally disqualified Type 4 hemispheres tested in this report surpassed 500 cycles to 9,000-psi external pressure, post-service inspection of these two units revealed substantial differences in the extent of fatigue cracking that had occurred in the bearing-surface region of each component. The dimensionally qualified unit was found to have one small region of crack growth adjacent to its bearing surface, where as, the dimensionally disqualified hemisphere had extensive internal delaminations around the entire circumference of its bearing surface. Possible explanations for the apparent discrepancies in the performance of these two units are offered as follows:

   - Differences in the ceramic material in these two hemispheres could explain the differences in the amount of crack growth that occurred. Specifically, differences in the fracture toughness, flexural strength, Weibull Modulus, residual stress, intrinsic porosity, or extrinsic grinding damage on the bearing surface of each part could affect its resistance to the formation of fatigue cracks. Unfortunately, material properties and quality control data were not obtained for the disqualified unit because it was not originally intended for pressure testing.

   - The quality of the seal that was used to protect the epoxy bond between the metallic joint ring and cylindrical skirt of the ceramic hemisphere from water intrusion could affect the end closure's structural

[2]NRaD was previously Naval Ocean Systems Center (NOSC).

performance. If the epoxy bond is not adequately sealed during extensive pressure testing, it is possible that the combination of water and tensile stresses in the bearing surface region could accentuate fatigue of the ceramic through stress corrosion cracking.

CONCLUSIONS

1. Monocoque ceramic cylinders with 25-inch-OD by 31.90-inch-length by 0.90-inch wall thickness with mating ceramic hemispheres can be successfully fabricated from isostatically pressed 96-percent alumina for service as components of an external pressure housing for 9,000-psi service.

2. Full-immersion pulse-echo ultrasonic inspection has been found to be a reliable NDE technique for detection of voids and inclusions larger than 0.015 of an inch in the walls of alumina pressure hull components of <1-inch thickness.

3. Monocoque alumina cylinders can be assembled into long cylindrical full-scale housings by epoxy bonding the ends of the adjoining cylinders to titanium joint rings with integral ring stiffeners. The design of cylindrical hull sections with stiffened joint rings to provide the desired safety margin against failure by buckling can be performed using standard structural analysis techniques (references 1 and 2).

4. Although cyclic fatigue data was not obtained for the 25-inch-OD alumina cylinders (L/OD = 1.276, t/OD = 0.036) used in the 26-inch-housing cylindrical hull assembly, extensive pressure-test data has been generated (reference 4) for 12-inch-OD isostatically pressed AL-600 cylinders (L/OD = 1.5, t/OD = 0.034). At 9,000-psi external pressures, the 12-inch-OD cylinders were found to have a cyclic fatigue life of well in excess of 1,000 dive cycles. Similar data needs to be generated for the 25-inch-OD cylinders as has been generated for 12-inch-OD cylinders and the 25-inch-OD hemispheres documented in this report. For this reason, it is suggested that prior to being placed into service, a qualification test program based on determining fatigue life be completed for 25-inch-OD monocoque alumina cylinders subjected to external pressure cycles.

5. The design of the aft and forward head has been validated for operational use as end closures for the 26-inch-OD housing for use at depths to 20,000 feet (9,000 psi) with a minimum fatigue life of 500 dive cycles. The key design features of these enclosures, ceramic cylindrical equatorial skirt, titanium end-cap joint rings, and titanium inserts for port penetrations, should be incorporated into future pressure-housing applications where ceramic hemispherical bulkheads are desired.

6. Full-scale UUV pressure housings using alumina-ceramic hull sections can be designed and assembled which provide improved operational performance over equivalent metallic housings designed to the same requirements. The net lift in seawater generated by the 26-inch-OD by 91-inch-long alumina-ceramic pressure housing is three times greater than that created by a rib-stiffened titanium housing with the same external dimensions and external pressure rating.

RECOMMENDATIONS

1. Pre-service inspection of alumina-ceramic pressure hull components should be made before final grinding is completed to avoid additional investment in parts that may have unacceptable internal defects. NRaD's experience in inspecting the 25-inch-OD hulls for the 26-inch housing indicates that isostatically pressed 96-percent alumina components can be fabricated of this size that do not contain flaws of which the dimensions exceed 0.05 inch.

2. As the acceptance of ceramic pressure hulls grows for ocean engineering applications in the future, periodic in-service inspection techniques should be developed to ensure the

structural integrity of the pressure housings throughout their operational lives. The use of portable hand-held ultrasonic thickness detectors has been shown to be a reliable means of finding internal discontinuities such as delaminations associated with extensive cyclic fatigue of ceramic pressure hulls. If a ceramic hull section is inspected and found to have crack growth that has extended meridionally in the shell wall beyond the encapsulating flanges of the metallic joint rings, it can be removed from further service and replaced with a new hull.

3. The majority of research performed for ceramic pressure housings to date has focused on determining designs that will perform successfully for external pressure loads associated with the full range of depths found in the world's oceans. In order to gain further acceptance by the ocean engineering community, the capabilities of ceramic pressure-housing assemblies to withstand dynamic loading associated with handling should also be characterized.

4. Research should be initiated that has as its goal the development of an economical nondestructive inspection procedure for the detection and measurement of residual stresses in ceramic components introduced by the sintering process.

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GLOSSARY

AL-600	WESGO. 96-percent aluminum oxide composition
alumina	aluminum oxide
ASL	Arctic Submarine Laboratory
FEA	finite element analysis
FEM	finite element models
flexural strength	modulus of rupture
GFR	graphite fiber-reinforced
ID	inside diameter
L	Length
L/OD	length-to-outer-diameter ratio
MEK	methyl ethyl ketone
MOR	modulus of rupture
NDE	nondestructive evaluation
NOSC	Naval Ocean Systems Center
OD	outside diameter
PEEK	poly-ether-ether-ketone
ROV	remotely operated vehicle
RTV	room-temperature vulcanizing sealant
SF	safety factor (factor of safety)
specific strength	strength-to-density ratio
SRI	Southwest Research Institute
t	thickness
t/OD	thickness-to-outer-diameter ratio
UUV	unmanned underwater vehicle
W/D	weight to displacement ratio

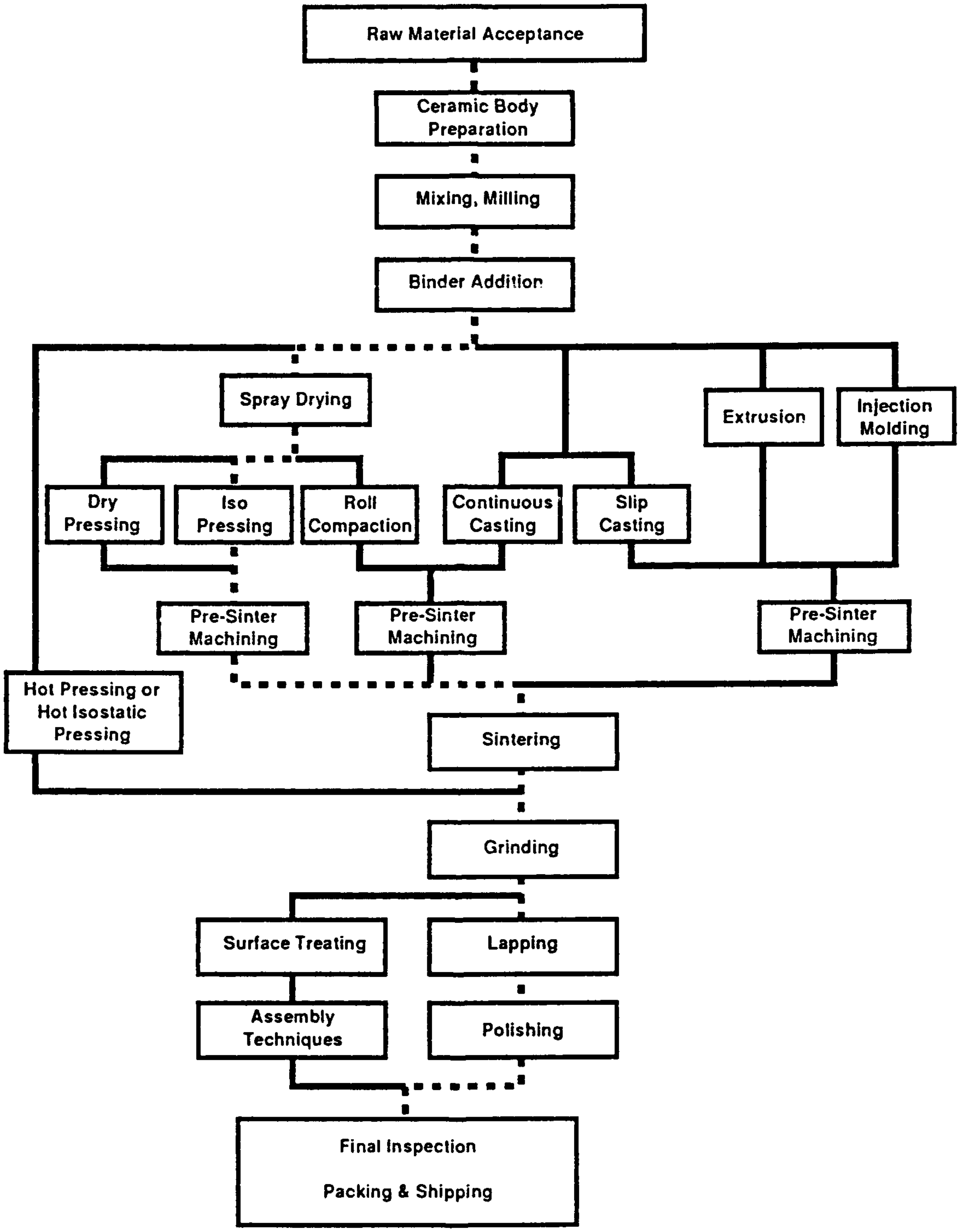


Figure 1. Manufacturing steps for alumina-ceramic parts.

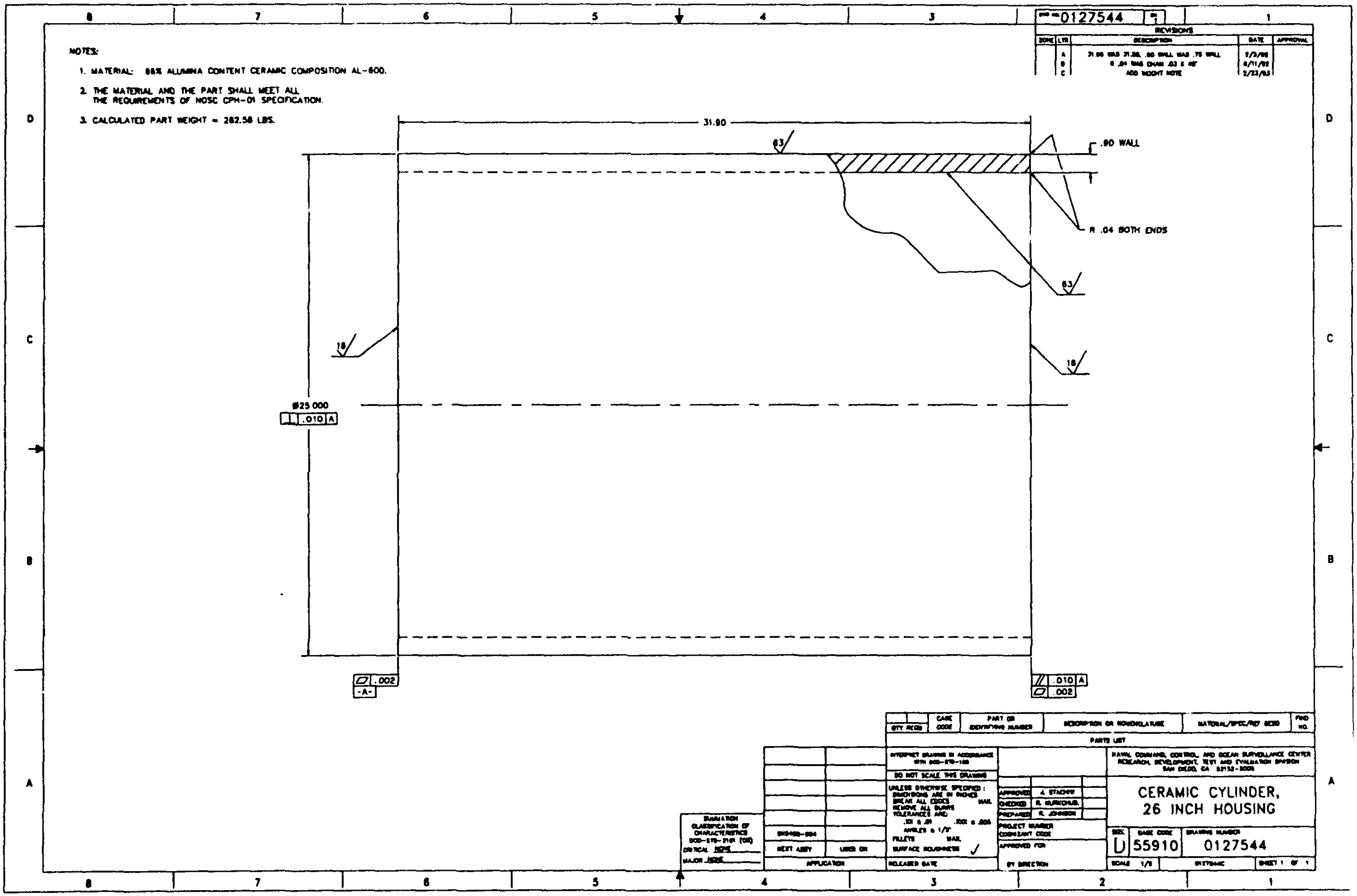


Figure 2. Engineering drawing of the 26-inch-housing alumina-ceramic cylinders.

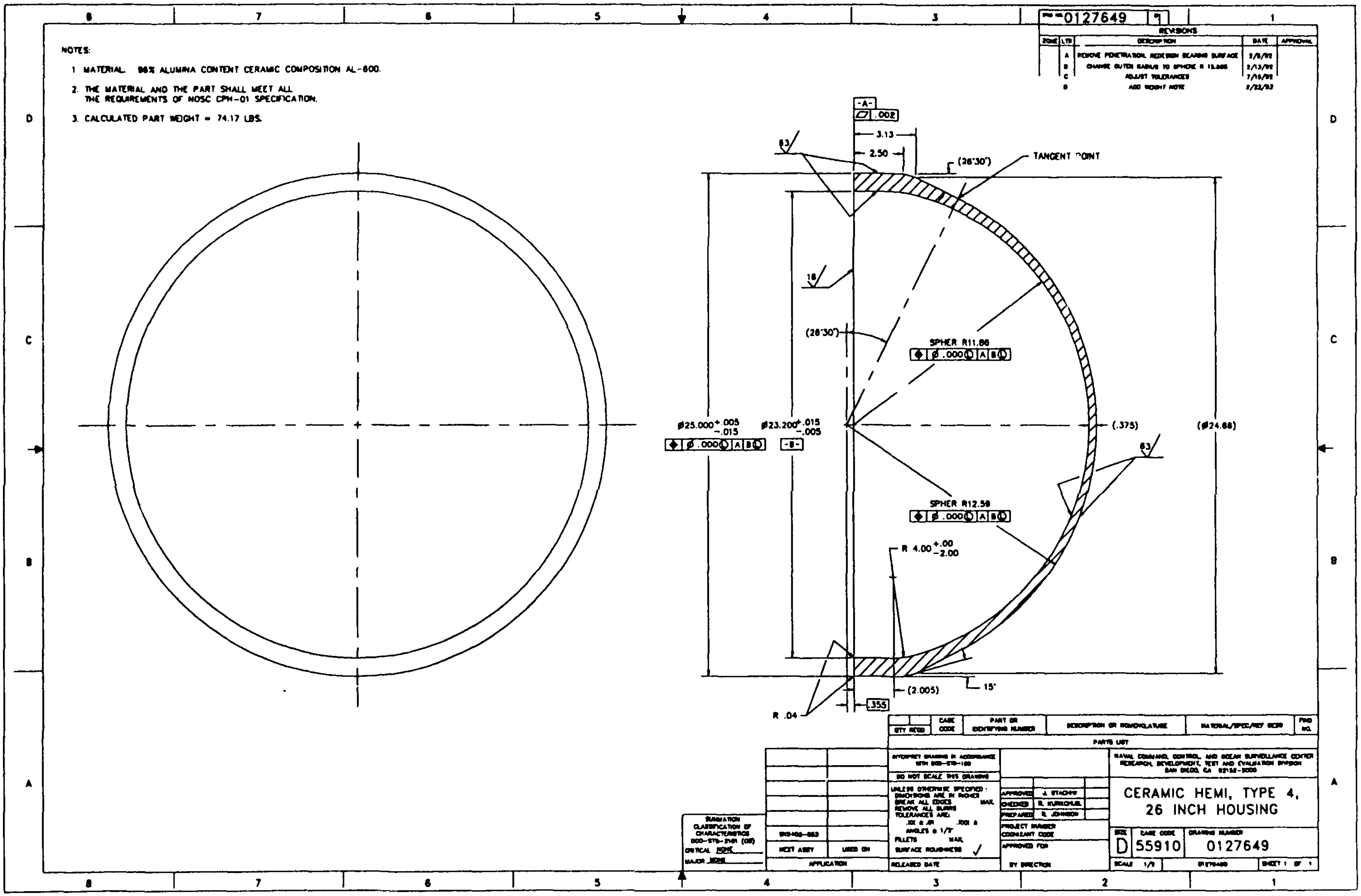


Figure 3. Engineering drawing of the 26-inch-housing alumina-ceramic Type 4 hemisphere.

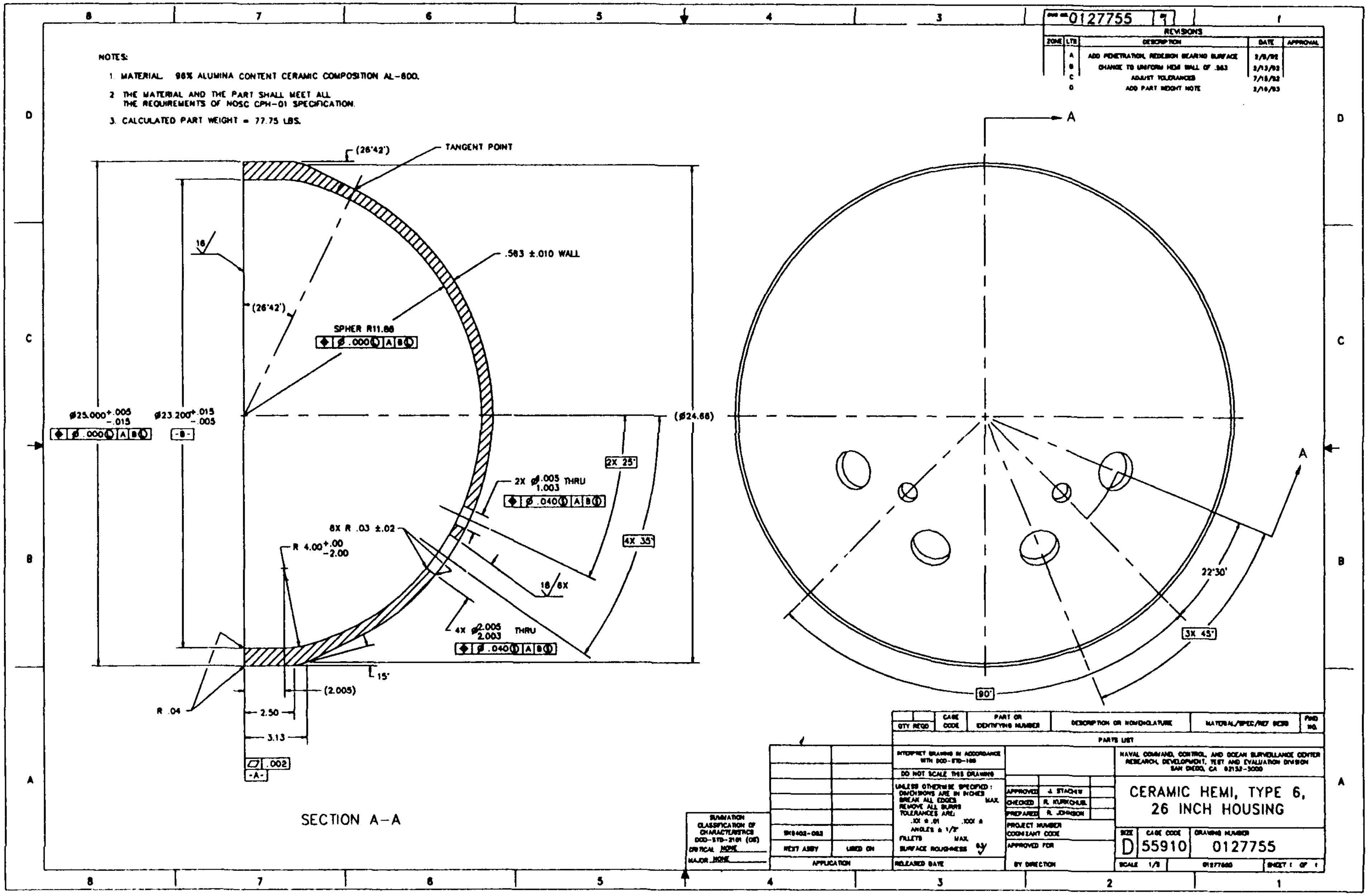


Figure 4. Engineering drawing of the 26-inch-housing alumina-ceramic Type 6 hemisphere.

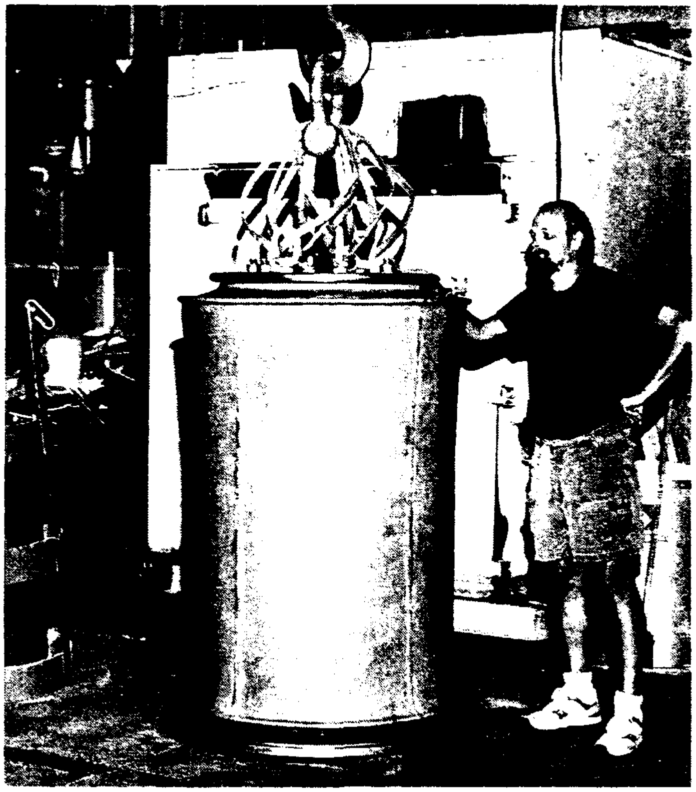


Figure 5. Isostatic pressing mold for 26-inch-housing alumina cylinders.

Figure 6. Hydrostatic pressure chamber used for pressing 26-inch-housing alumina components.

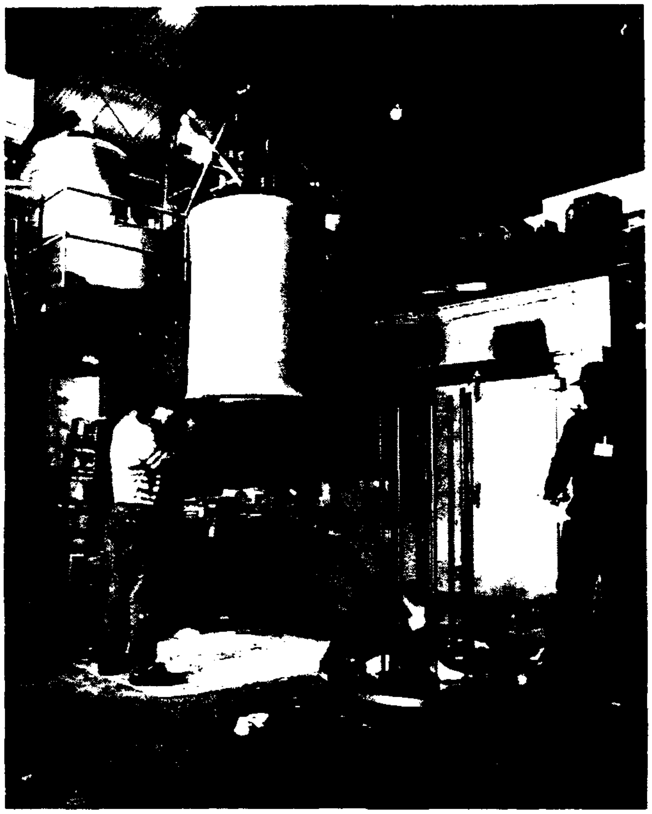


Figure 7. Removal of cylinder alumina green body from hydrostatic pressure chamber.

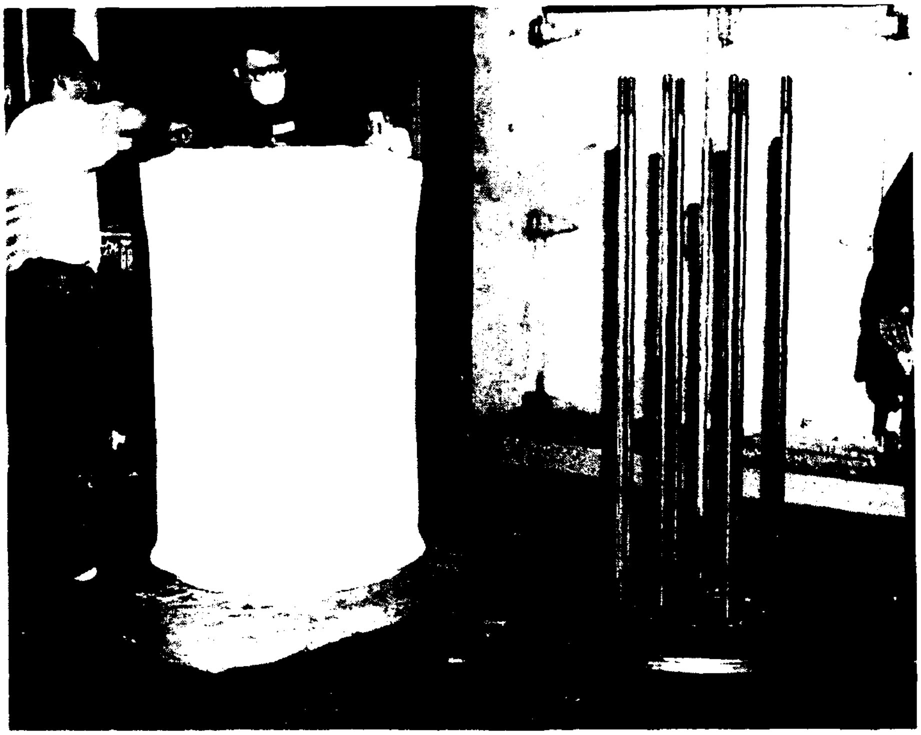


Figure 8. Removal of cylinder alumina green body from isopress tooling.

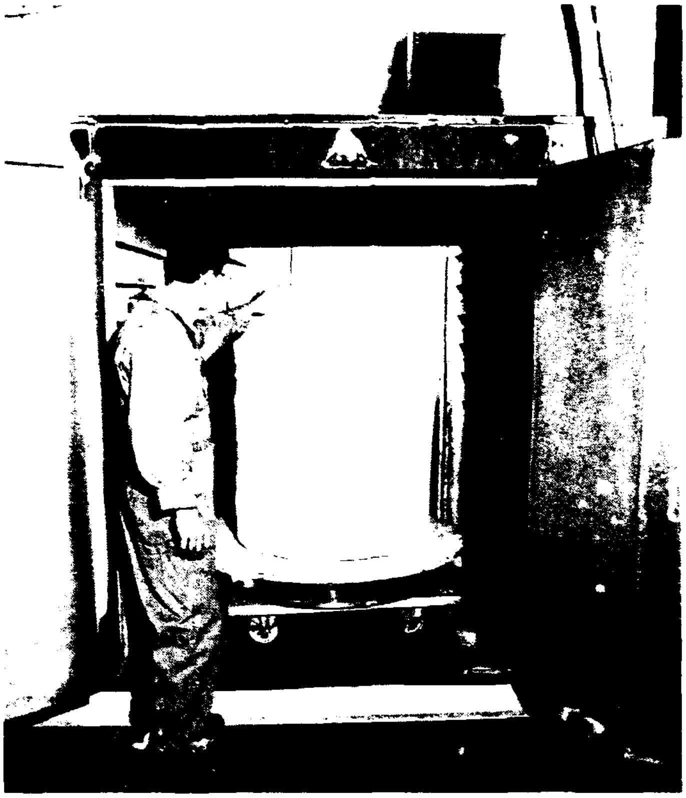


Figure 9. Isostatically pressed alumina-ceramic green body for 26-inch-housing placed in an oven for low temperature bakeout.

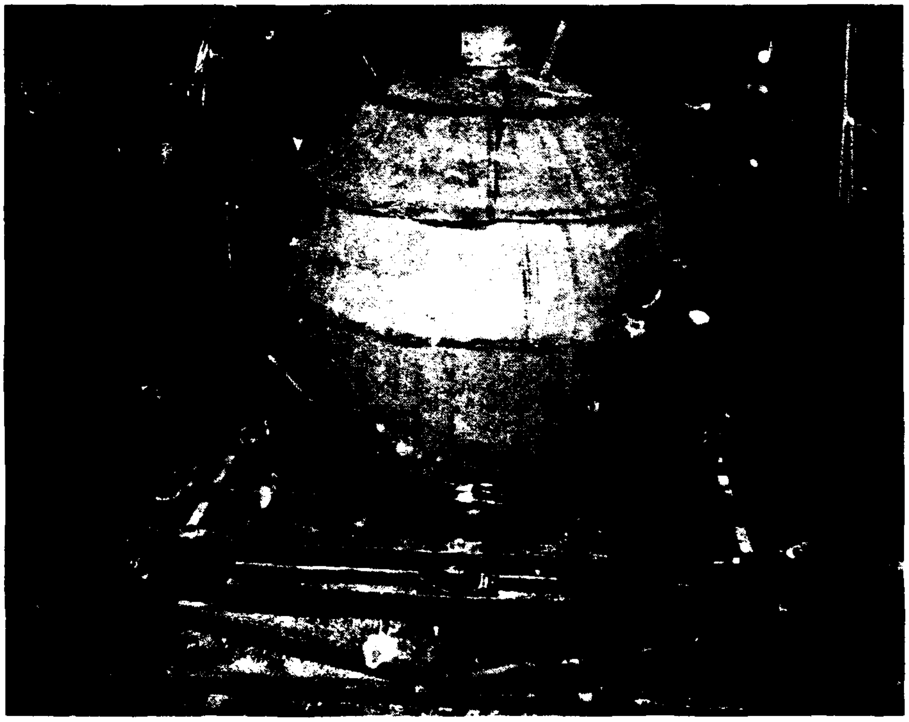


Figure 10. Isostatic pressing mold for ?6-inch housing alumina hemispherical end closures.

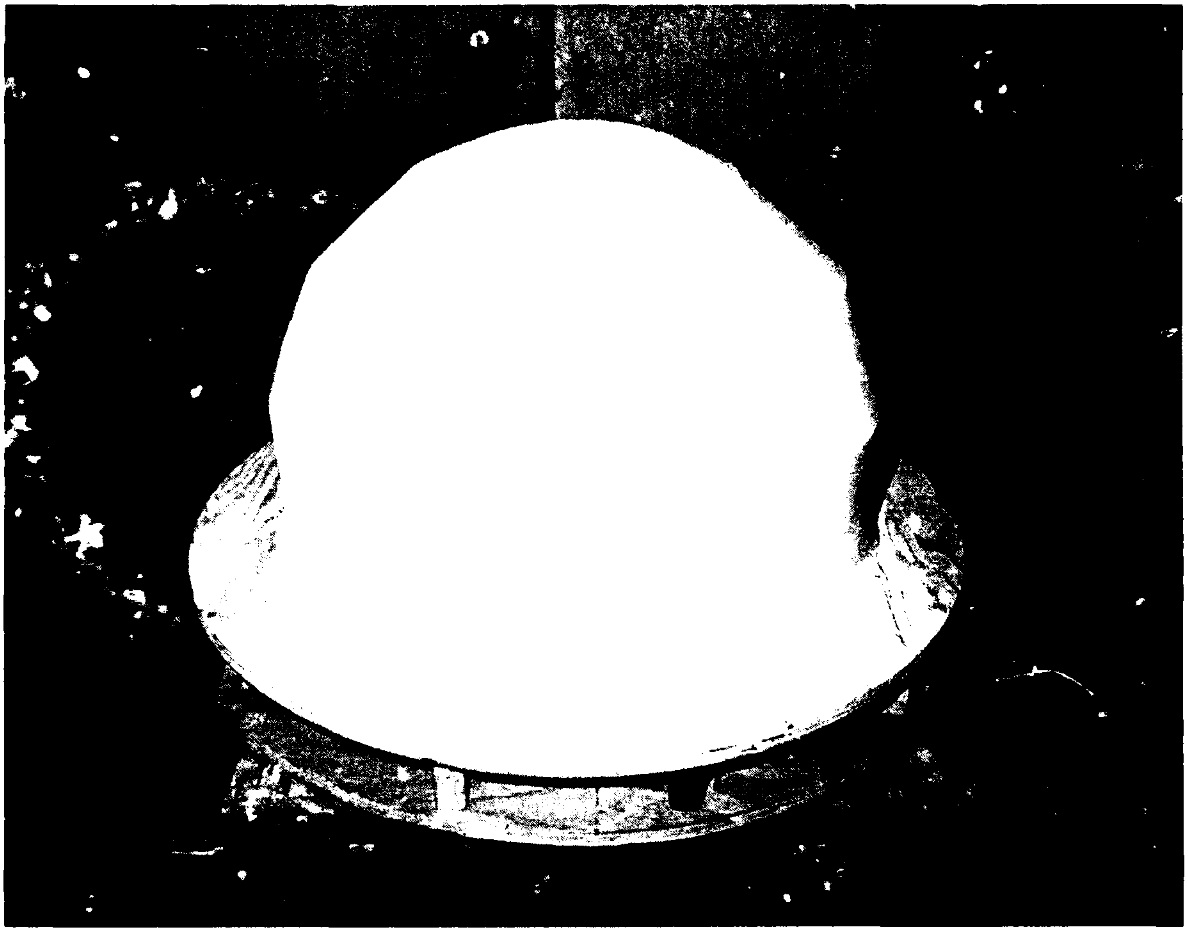


Figure 11 Isostatically pressed alumina green body for forward and aft head hemispherical end closures.

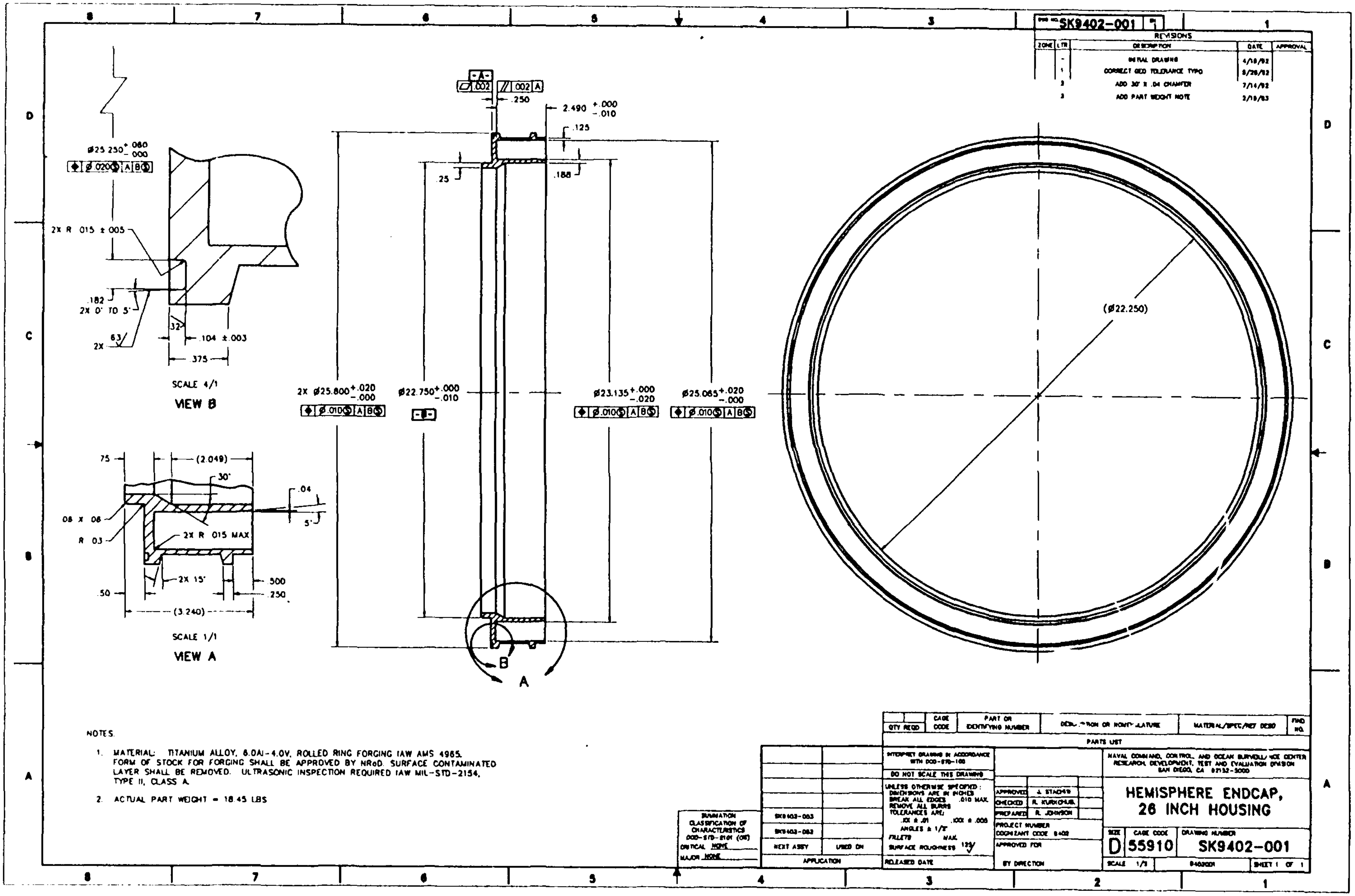


Figure 12. Engineering drawing of the 26-inch-housing hemisphere end-cap joint ring.

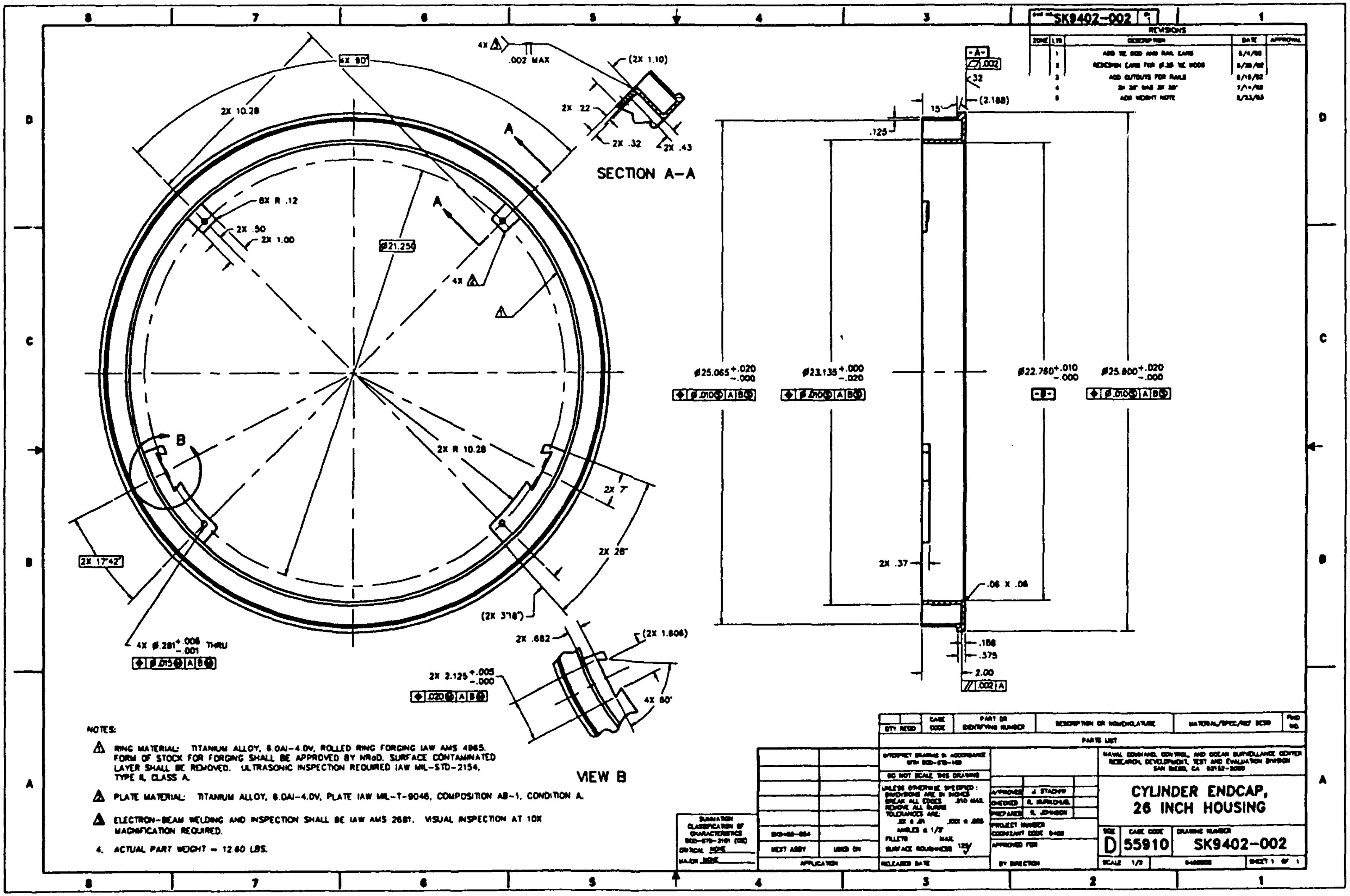


Figure 13. Engineering drawing of the 26-inch-housing cylinder end-cap joint ring.

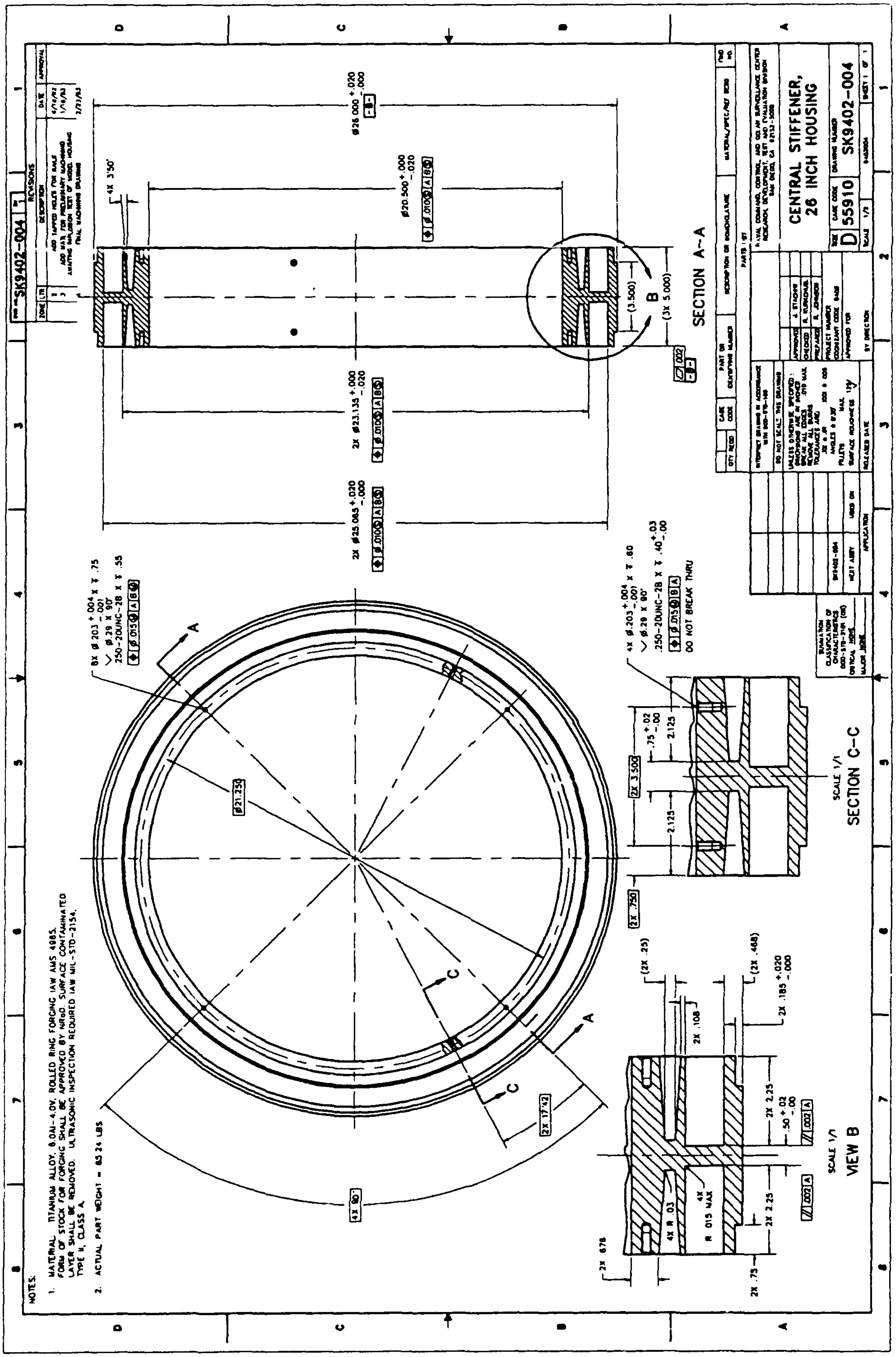


Figure 14. Engineering drawing of 26-inch-housing central stiffening joint ring.

Figure 15. Titanium alloy rolled ring forgings for 26-inch-housing joint rings.

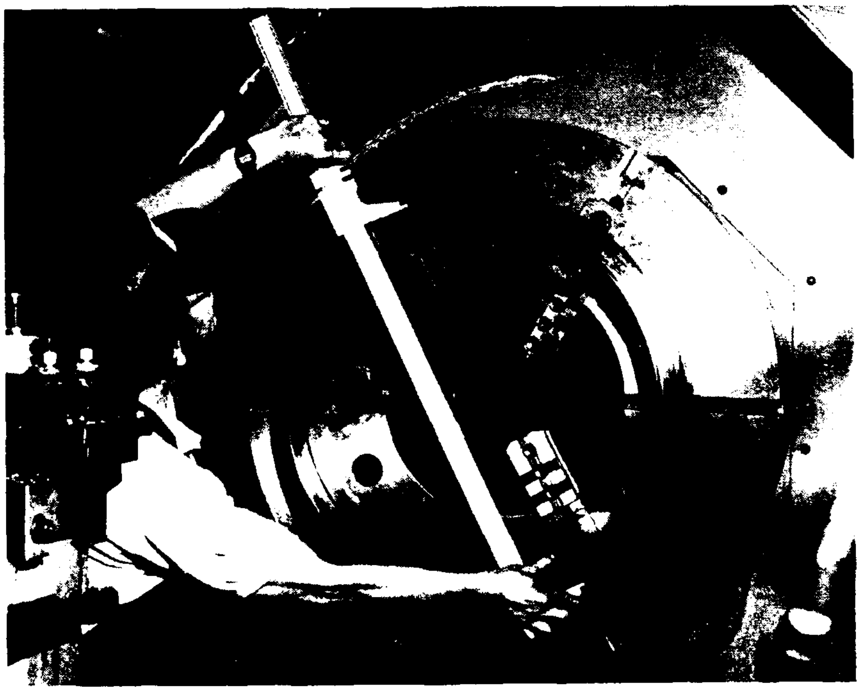


Figure 16. Machining of titanium end-cap joint ring for alumina hemispherical end closure.

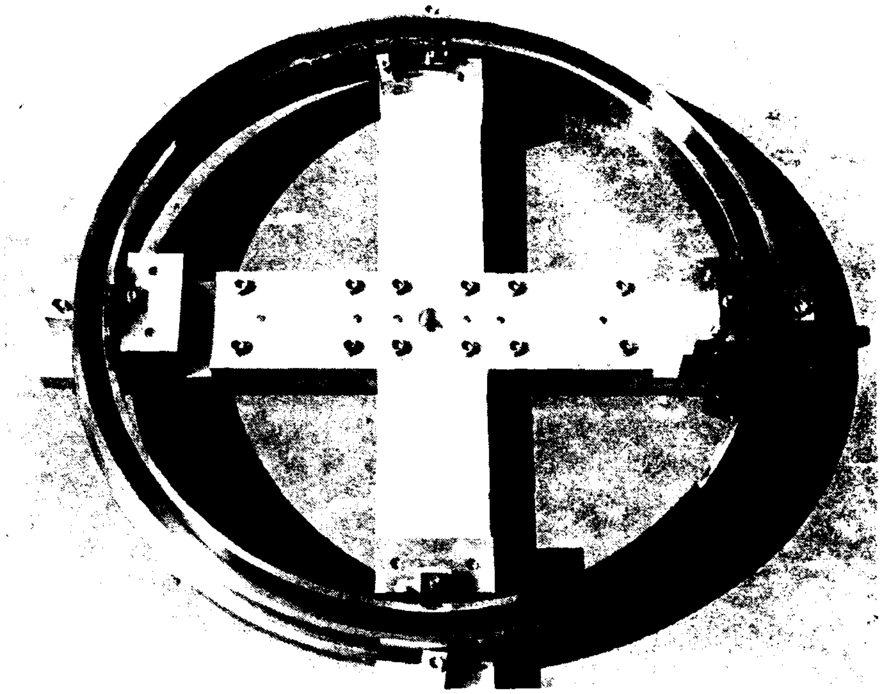


Figure 17. Welding fixture for titanium end-cap joint ring.

Figure 18. Cylinder end-cap joint ring.

Figure 19. Central stiffening joint ring.

Figure 20. Steel alloy billets for pressure test hemispherical end closures.

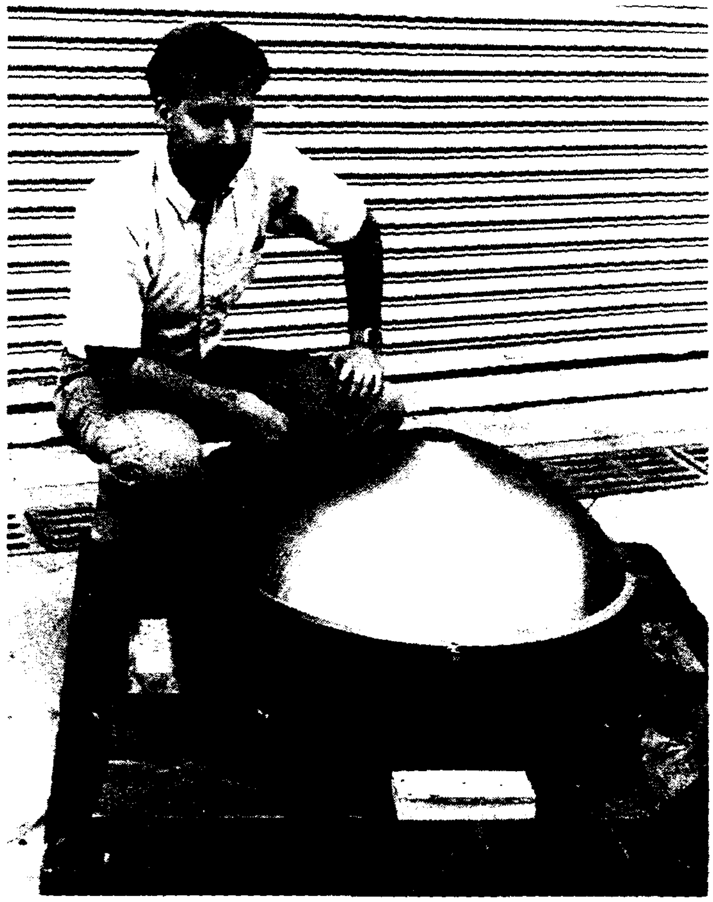


Figure 21. Steel hemispherical end closure.

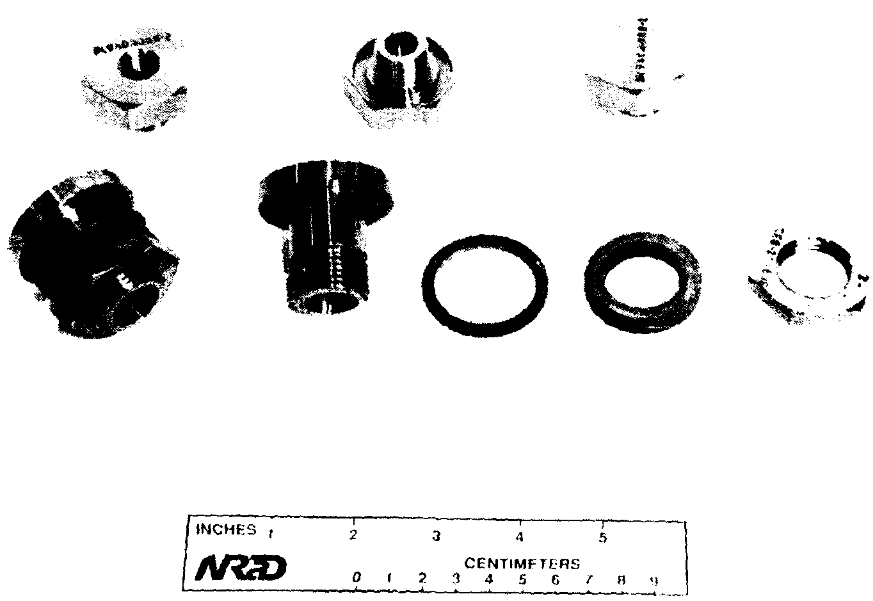


Figure 22. Inserts for pressure-relief valves in forward head assembly.

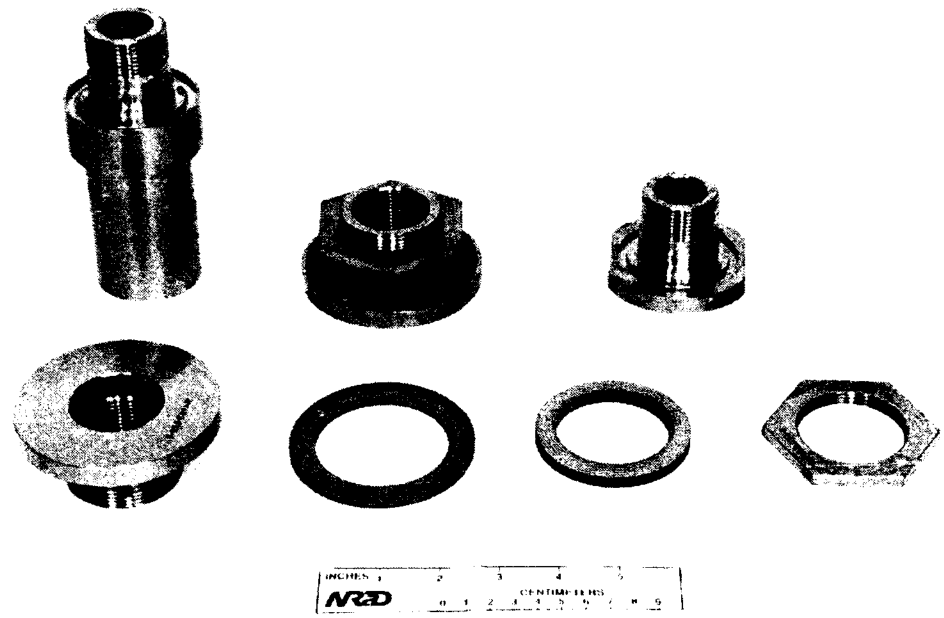


Figure 23. Inserts for electrical connectors in forward head assembly.

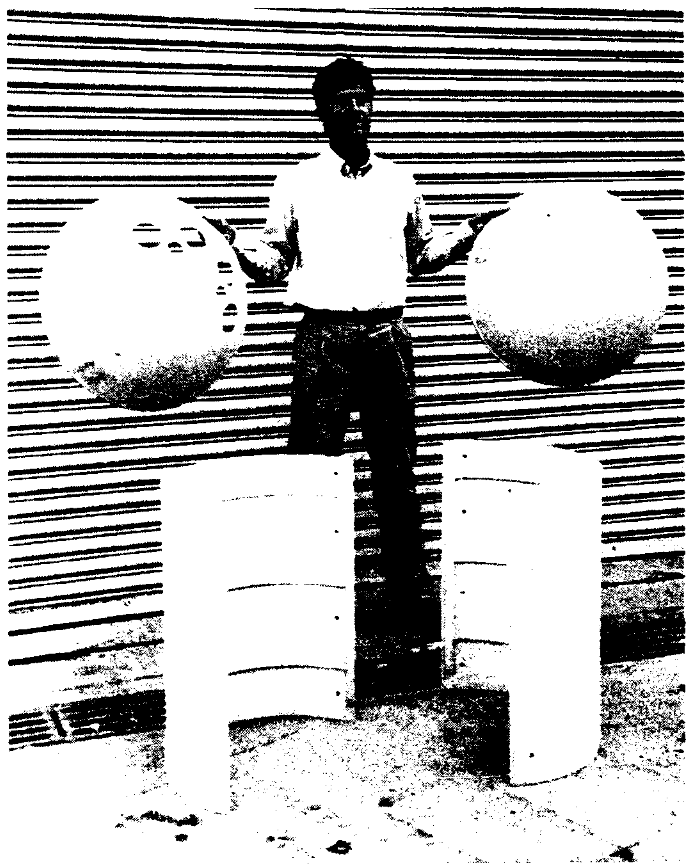


Figure 24. Composite fairing for 26-inch housing.

NOTES:

1. MATERIAL: WESGO AL-600 96% ALUMINA FIRED WITH PORE FORMER MATERIALS TO OBTAIN THE DEFECTS LISTED BELOW.

△ THE CODE USED BELOW FOR IDENTIFYING THE SURFACE CONDITION AND DEFECT TYPE SHALL BE ENGRAVED IN THE SURFACE OF EACH STANDARD IN THE APPROXIMATE POSITON SHOWN.

3. 26 INCH HOUSING CALIBRATION STANDARDS ARE TO BE USED FOR CALIBRATING NDE EQUIPMENT FOR INSPECTION OF THE 26 INCH HOUSING CERAMIC CYLINDERS 55910-0127544, CERAMIC HEMISPHERES 55910-0127949 AND 55910-0127755 AND SIMILAR ALUMINA CERAMIC COMPONENTS.

DEFECT TYPE	QTY. GROUND SURFACE -1 GEOMETRY	QTY. GROUND SURFACE -2 GEOMETRY	CODE
NONE	1	1	A1
.015 PORE	1	1	B1
.030 PORE	1	1	C1
.030 ROD (X 1.00 LONG)	1	1	D1
.50 PORE	1	1	E1
.100 PORE	1	1	F1
.125 PLANAR (X .005 THICK)	1	1	G1
.250 PLANAR (X .005 THICK)	1	1	H1

DEFECT TYPE	QTY. AS FIRED SURFACE -1 GEOMETRY	QTY. AS FIRED SURFACE -2 GEOMETRY	CODE
NONE	1	1	A2
.015 PORE	1	1	B2
.030 PORE	1	1	C2
.030 ROD (X 1.00 LONG)	1	1	D2
.50 PORE	1	1	E2
.100 PORE	1	1	F2
.125 PLANAR (X .005 THICK)	1	1	G2
.250 PLANAR (X .005 THICK)	1	1	H2

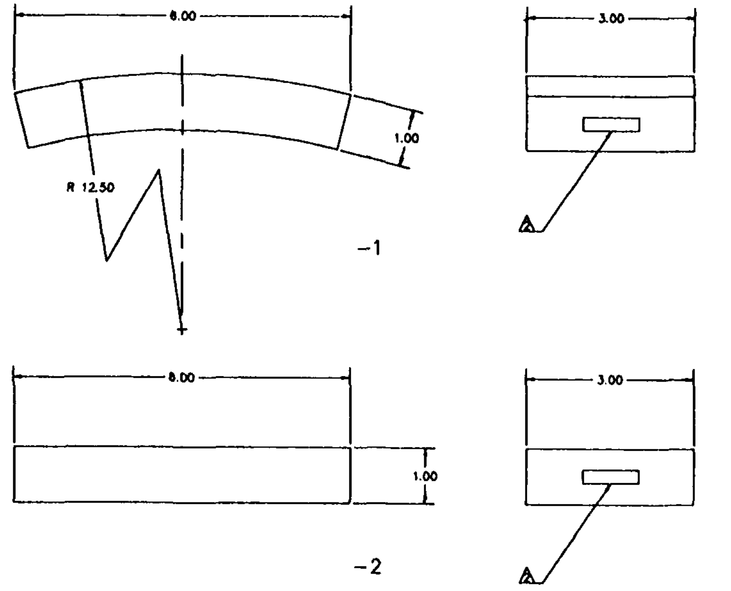


Figure 25. NDE calibration standards.

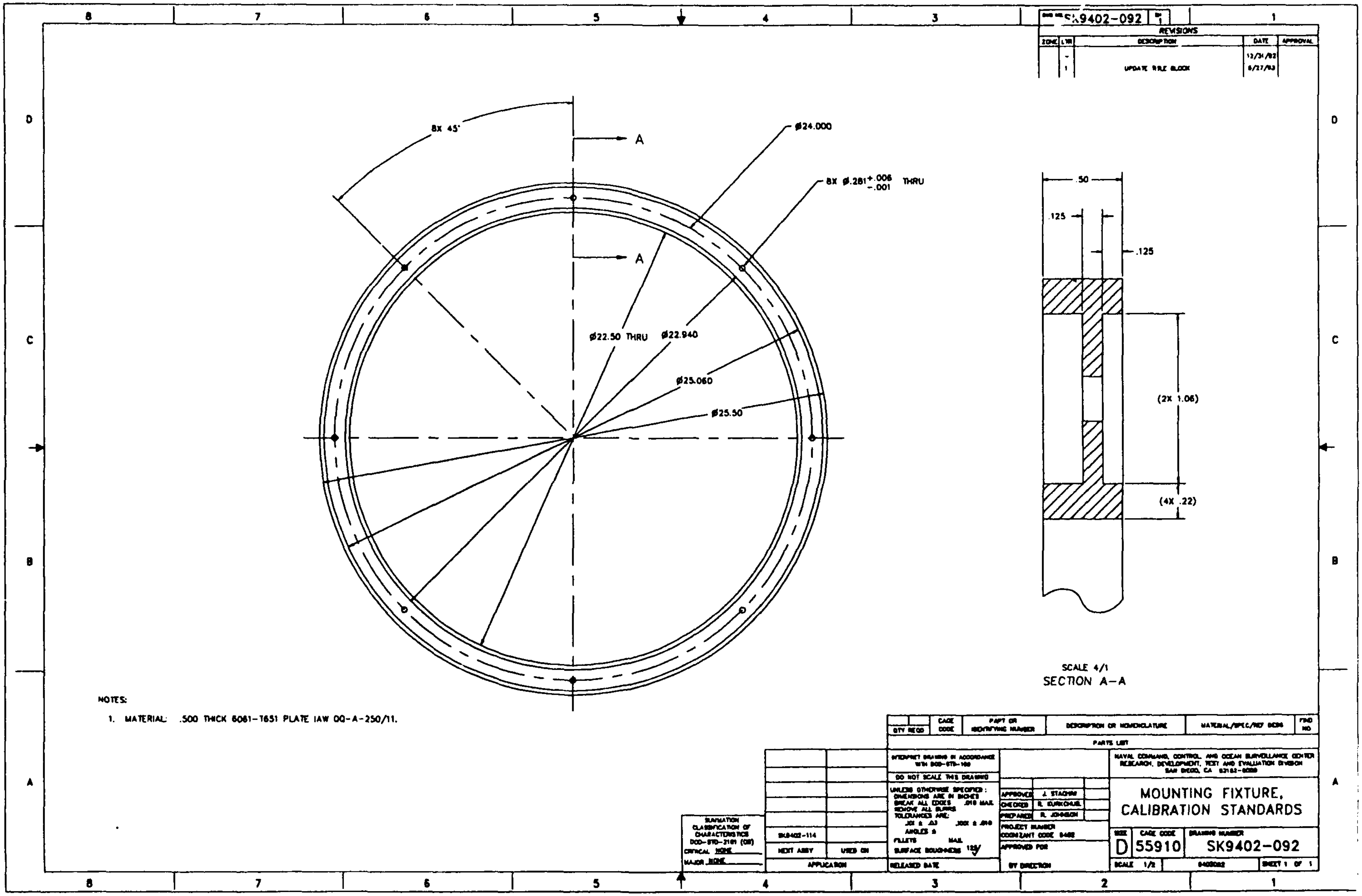


Figure 26. NDE calibration standard mounting fixture.

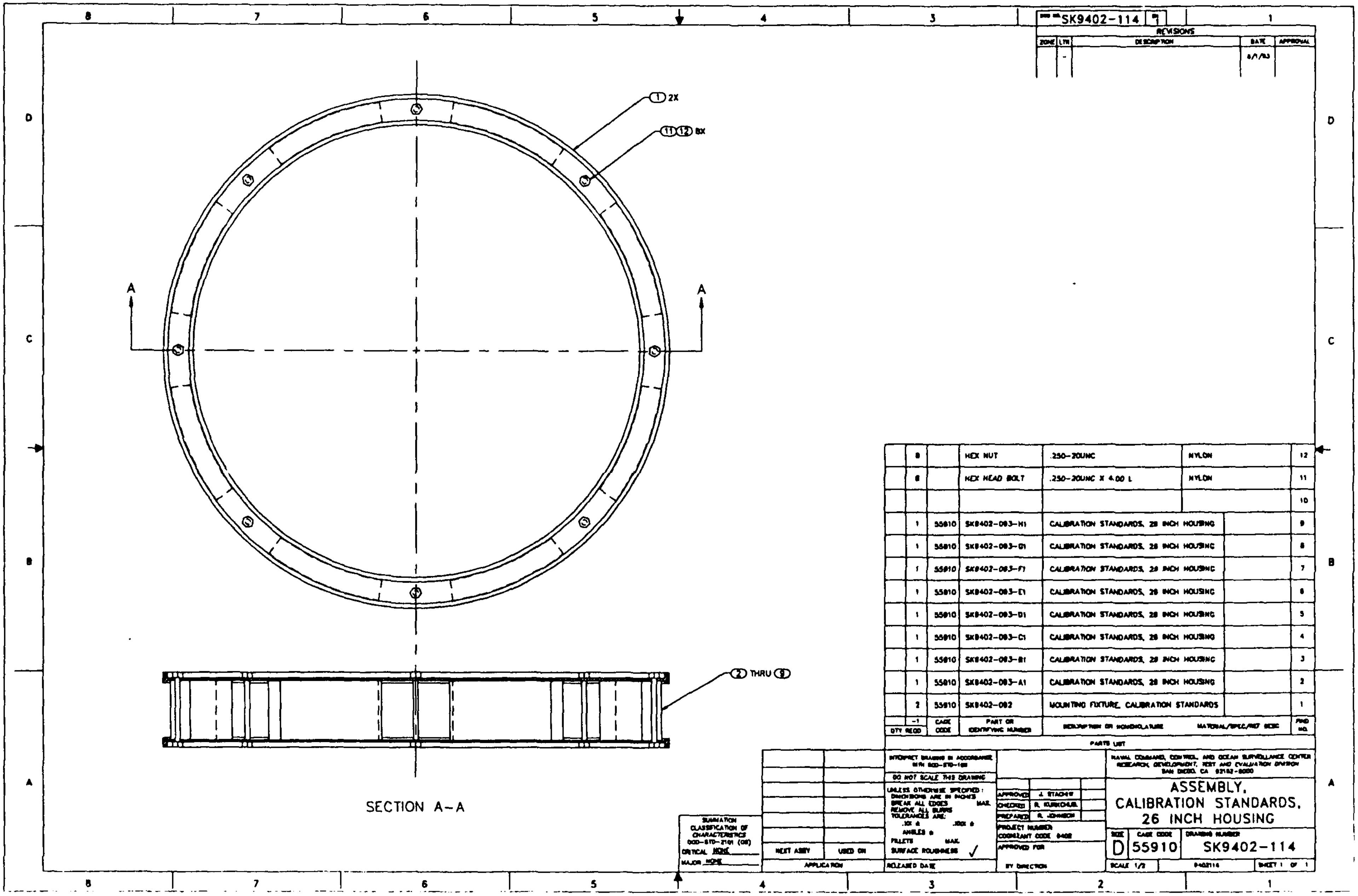


Figure 27. NDE calibration standard assembly.

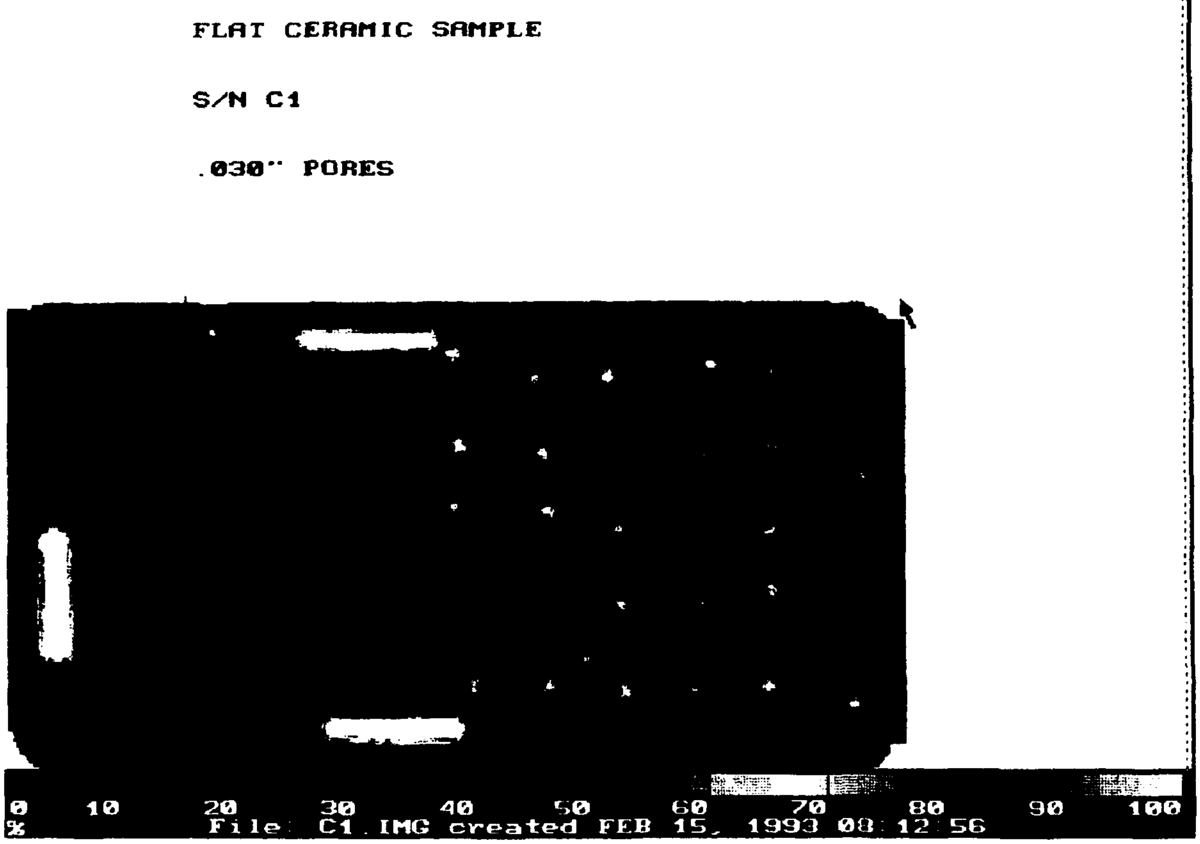


Figure 28. Pulse-echo ultrasonic C-scan of the 0.030-inch-pore NDE calibration standard.

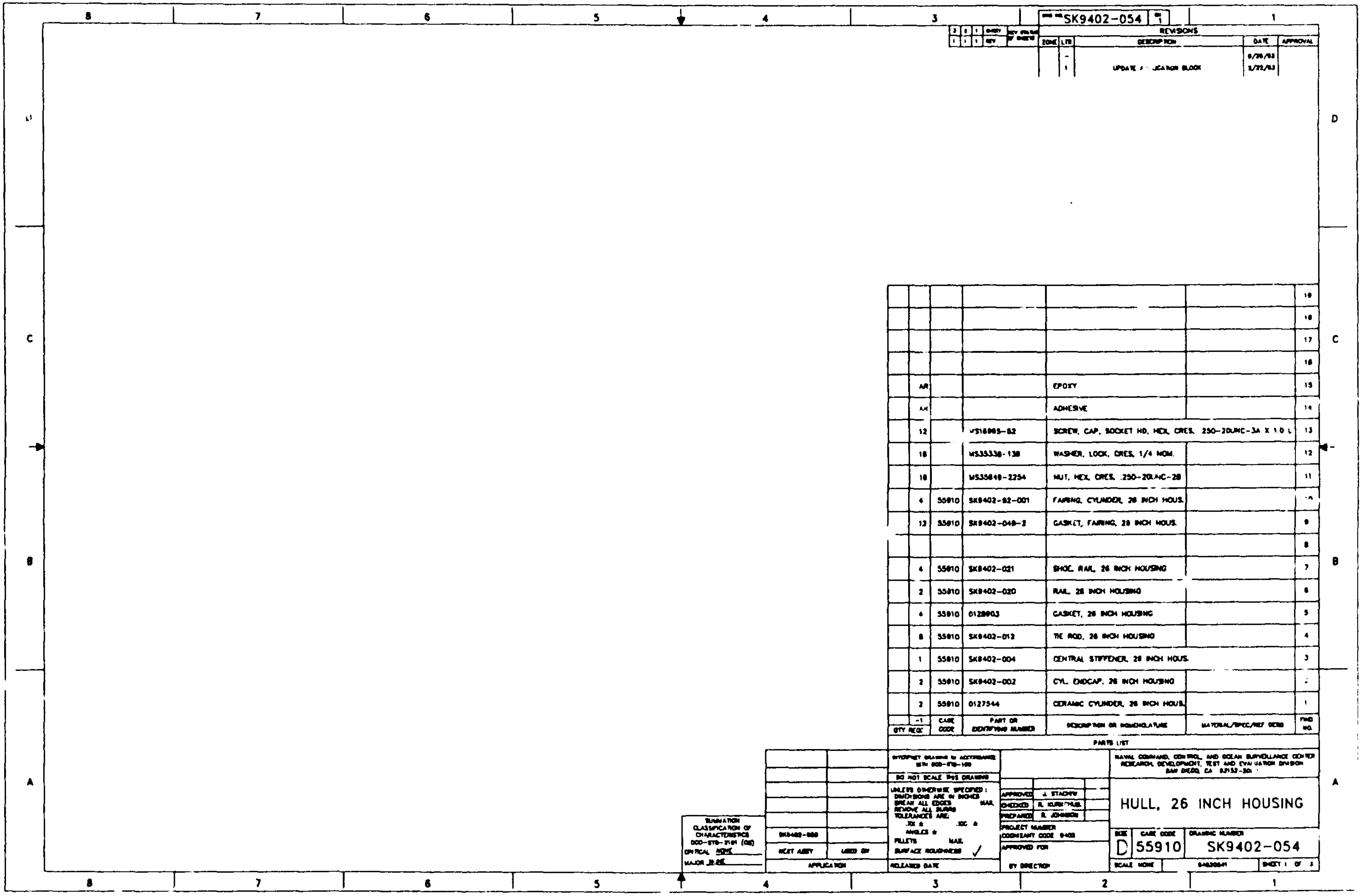


Figure 29. 26-inch-housing cylindrical hull, sheet 1.

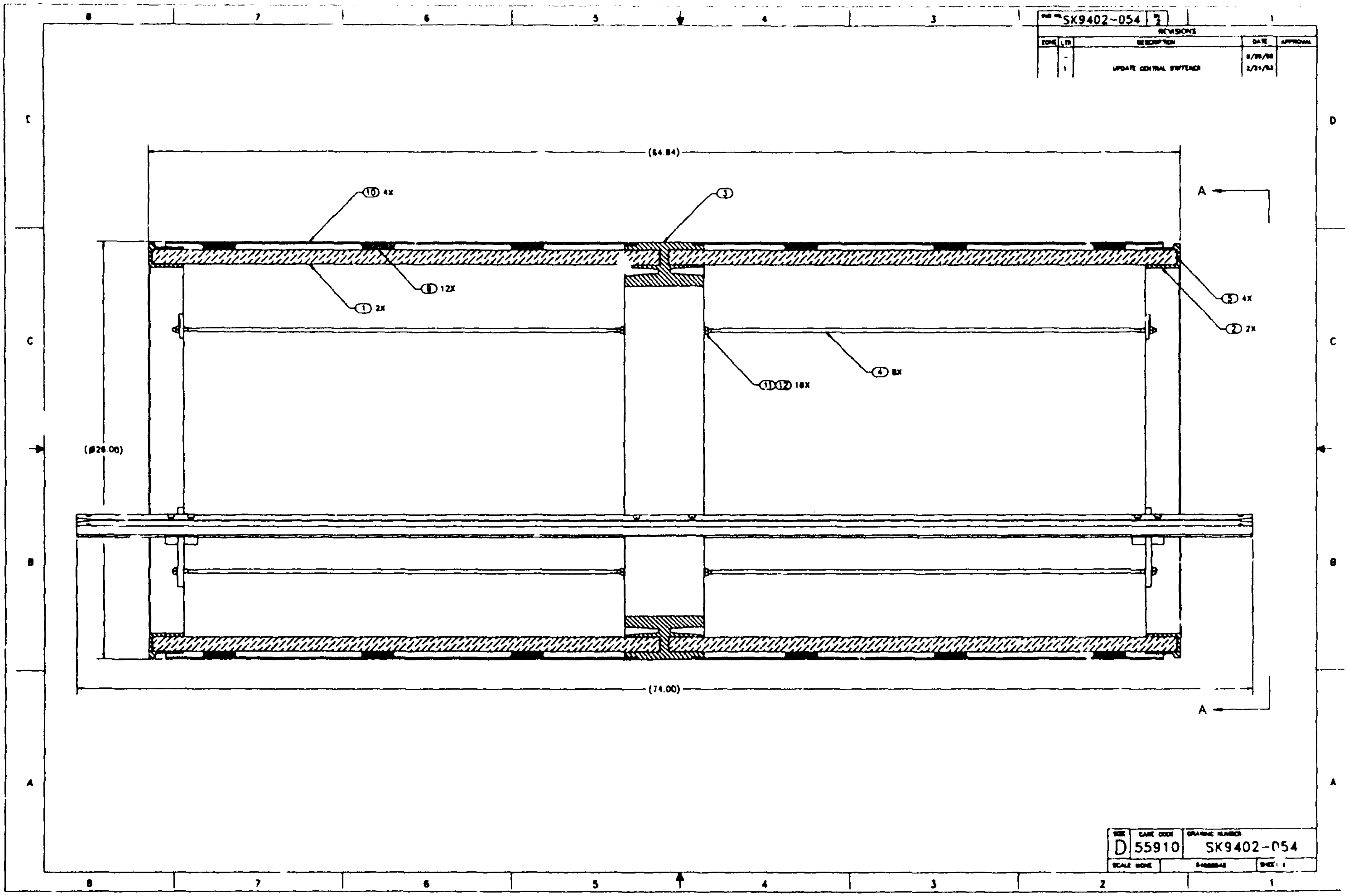


Figure 29. 26-inch-housing cylindrical hull, sheet 2.

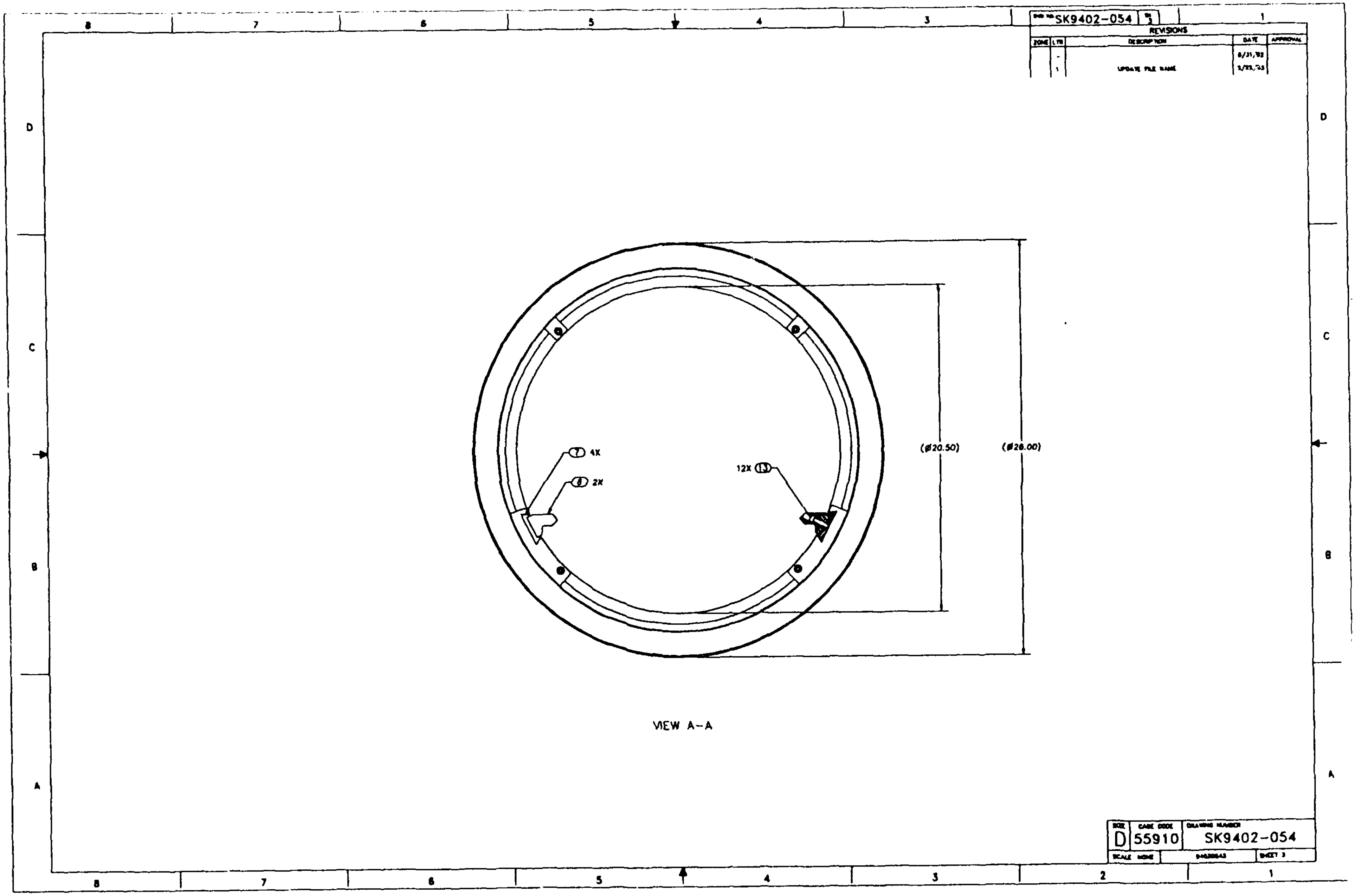


Figure 29. 26-inch-housing cylindrical hull, sheet 3.

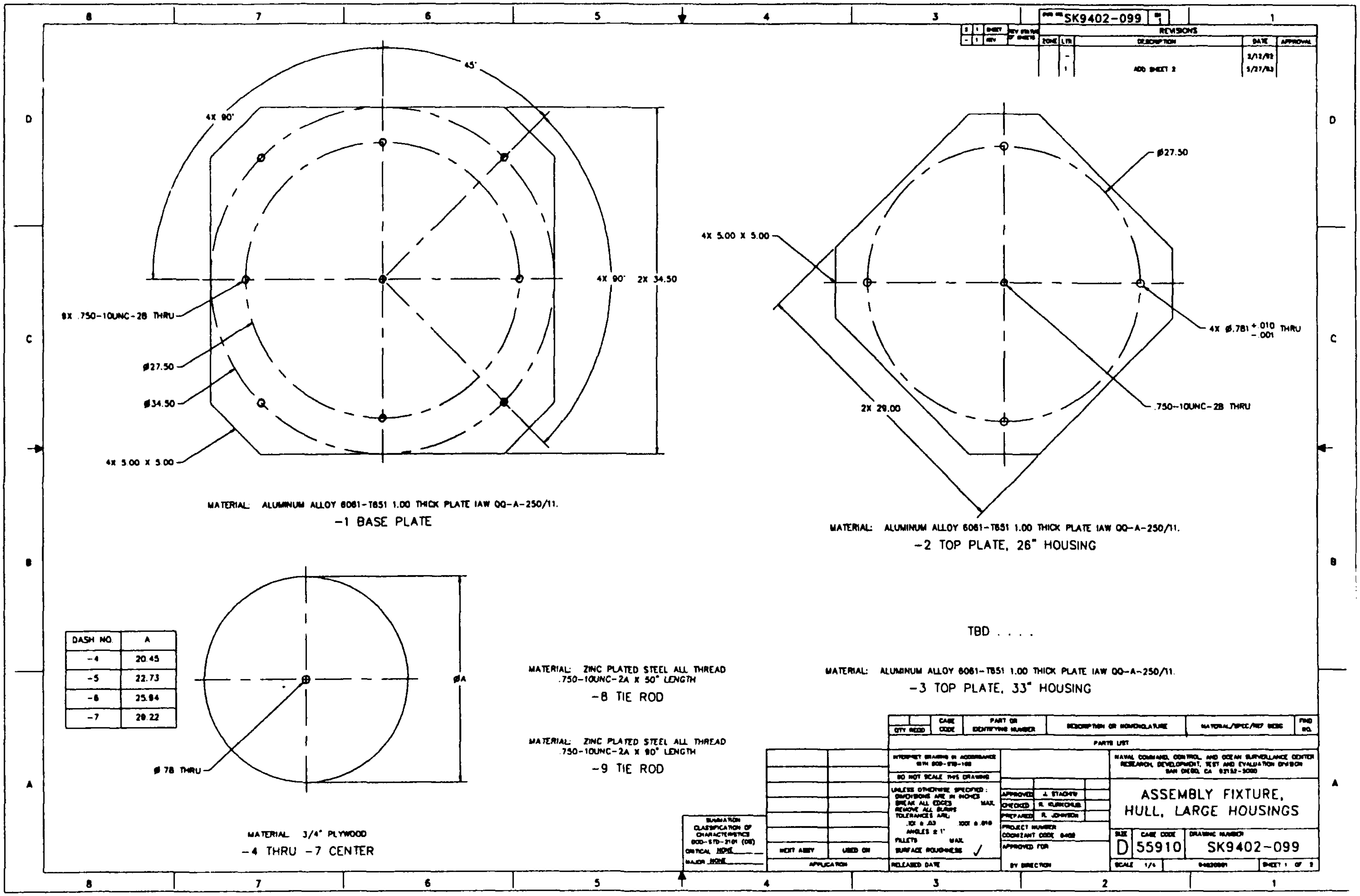


Figure 30. 26-inch-housing cylindrical hull assembly fixtures, sheet 1.

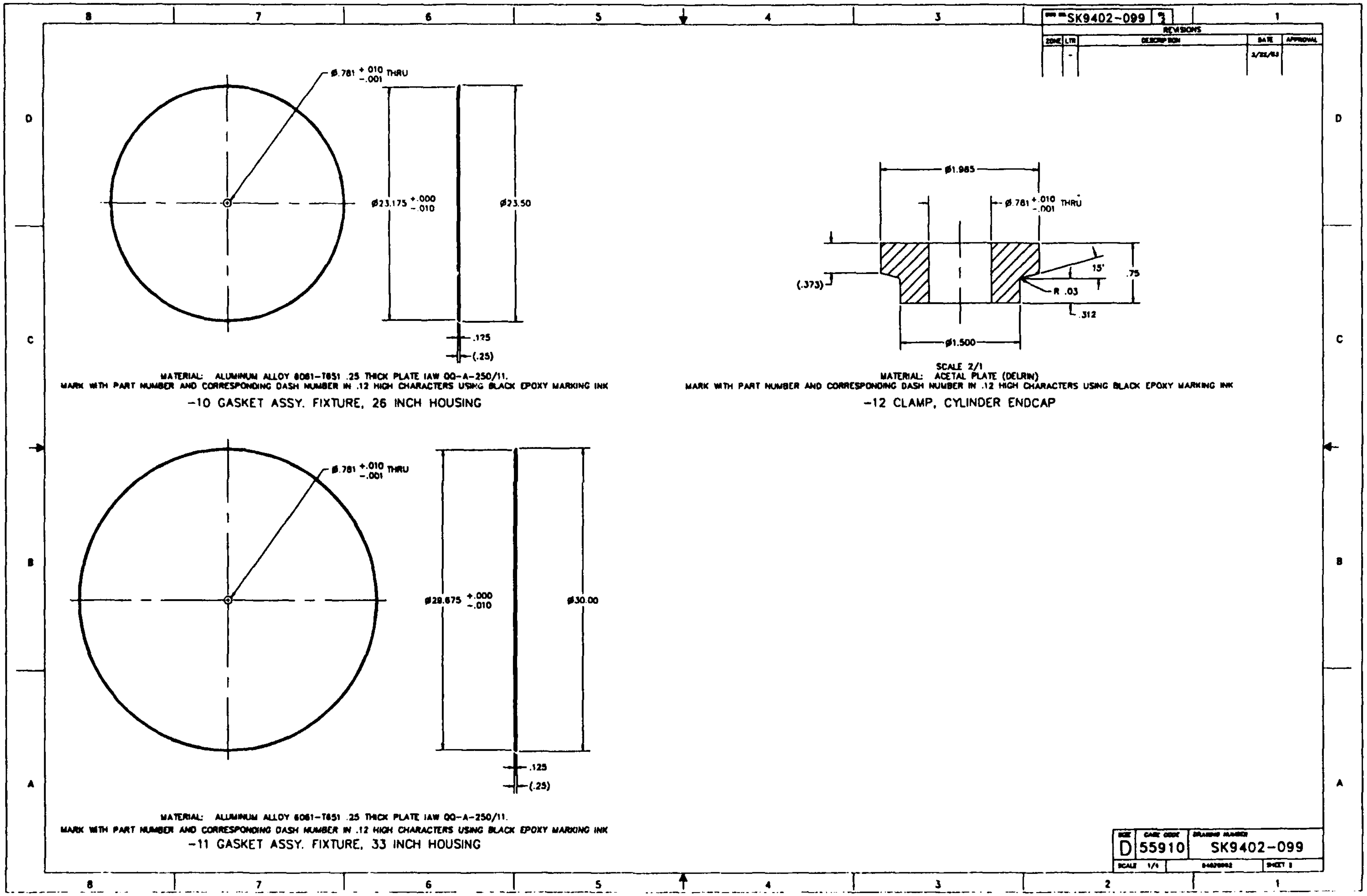


Figure 30. 26-inch-housing cylindrical hull assembly fixtures, sheet 2.

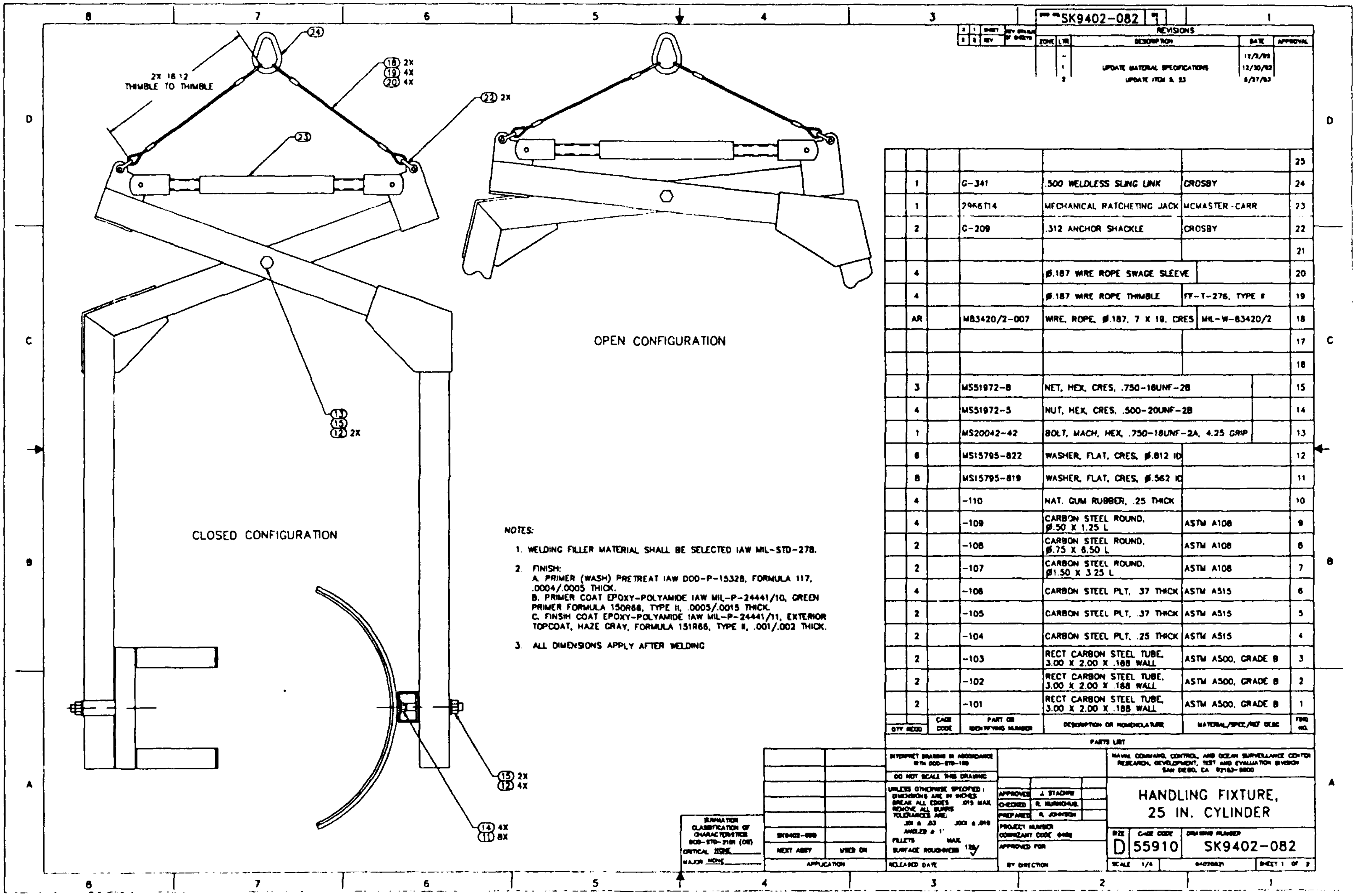


Figure 31. 26-inch-housing handling fixture, sheet 1.

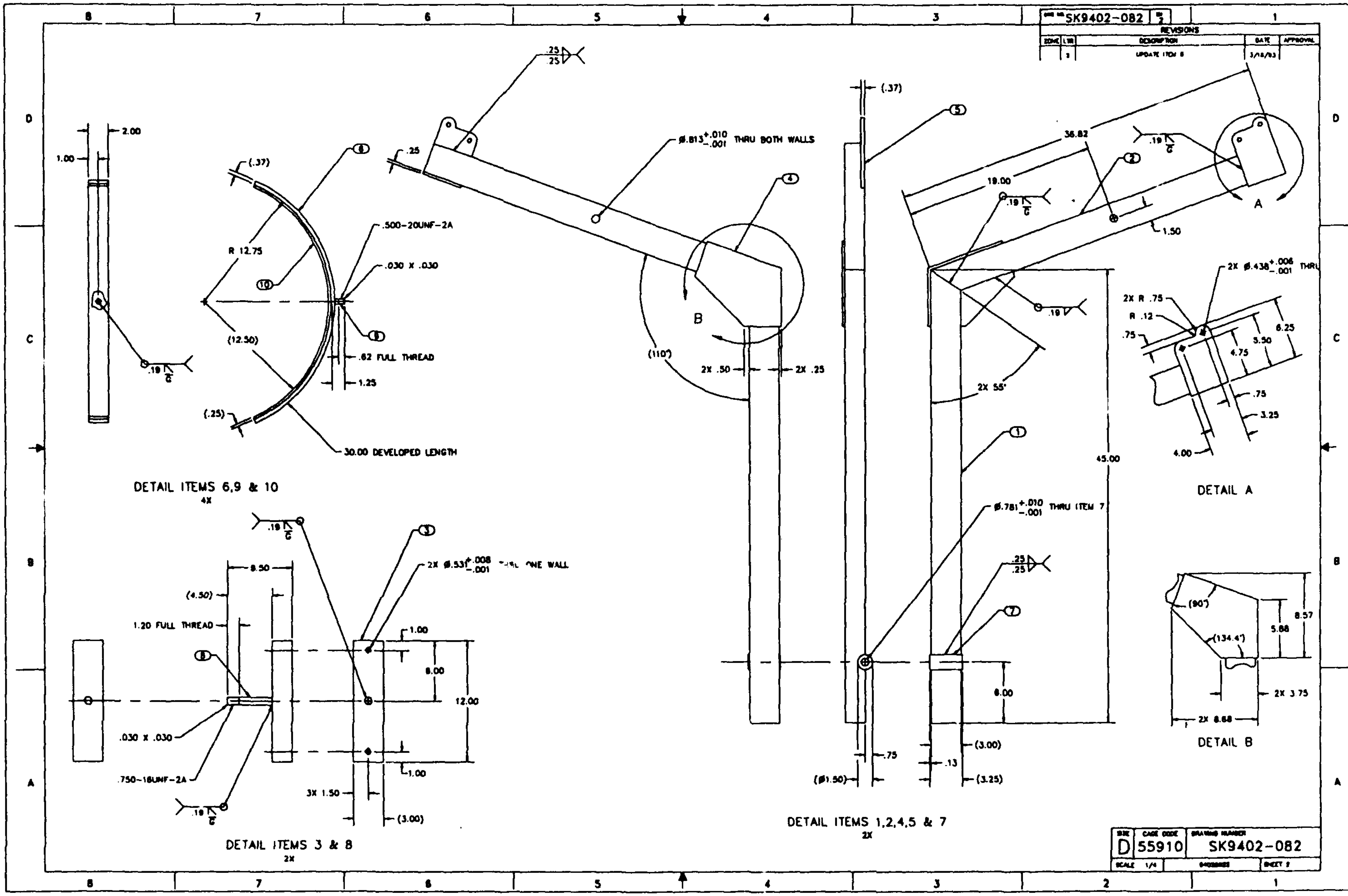


Figure 31. 26-inch-housing fixture, sheet 2.

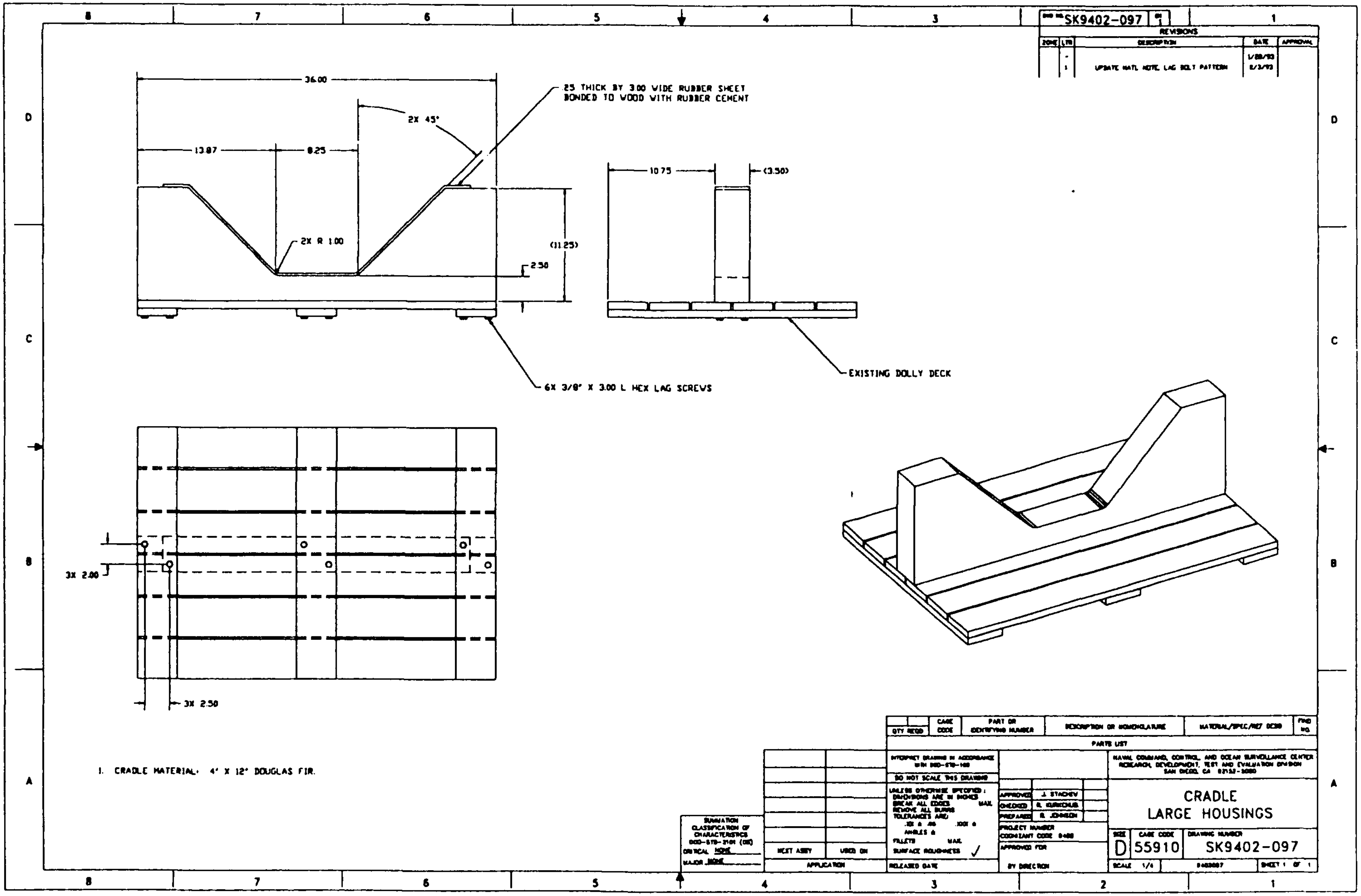


Figure 32. Handling cradles.

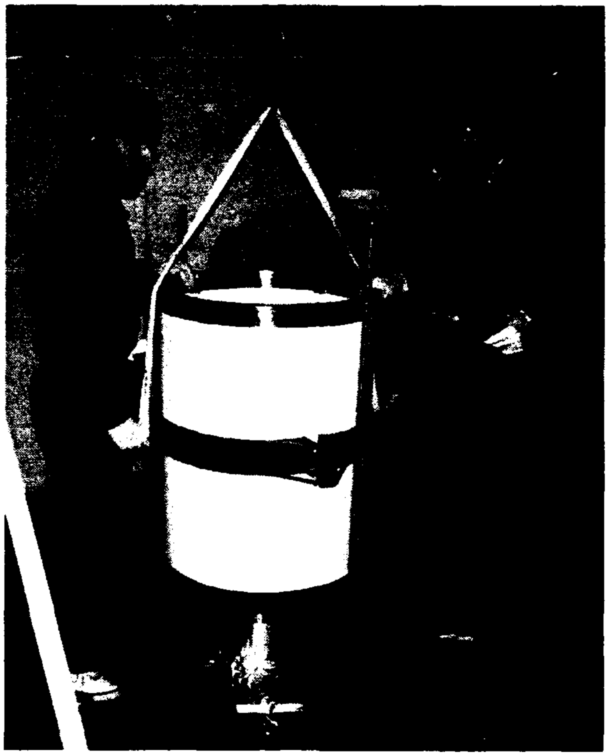


Figure 33. Epoxy bonding of central stiffening joint ring to first cylinder bay.

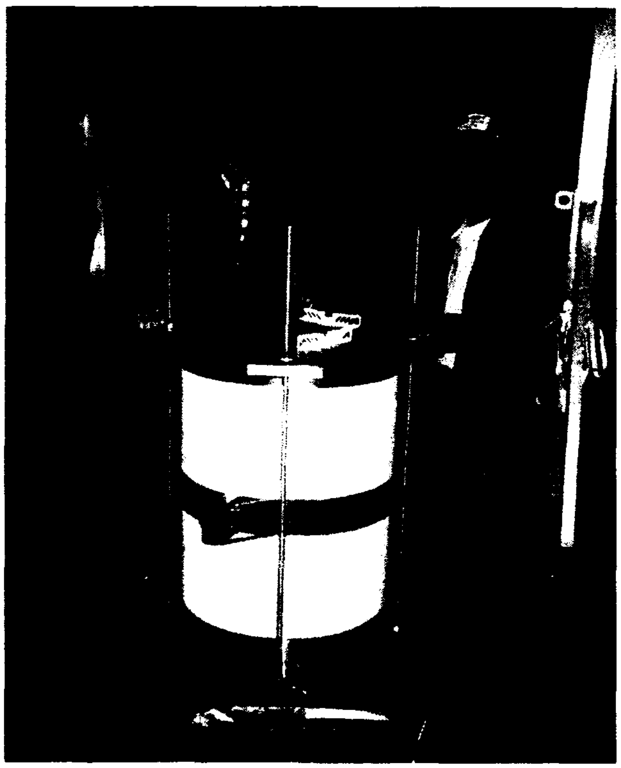


Figure 34. Epoxy bonded central stiffener with assembly fixtures.

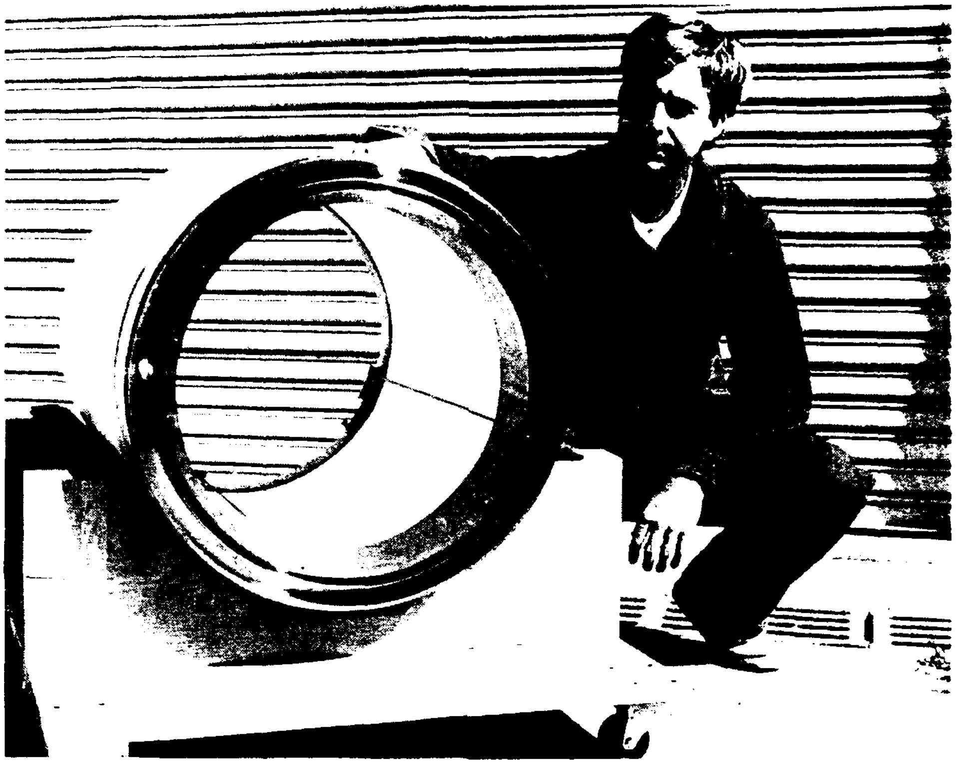


Figure 35. First bay of cylindrical hull.

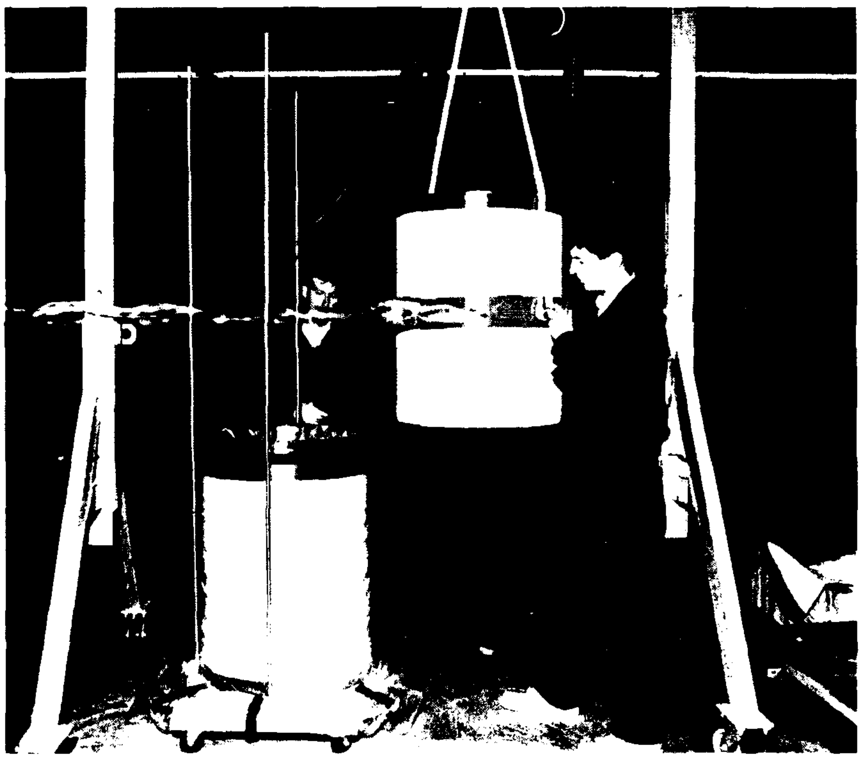


Figure 36. Assembly preparation for first and second bay of the cylindrical hull.

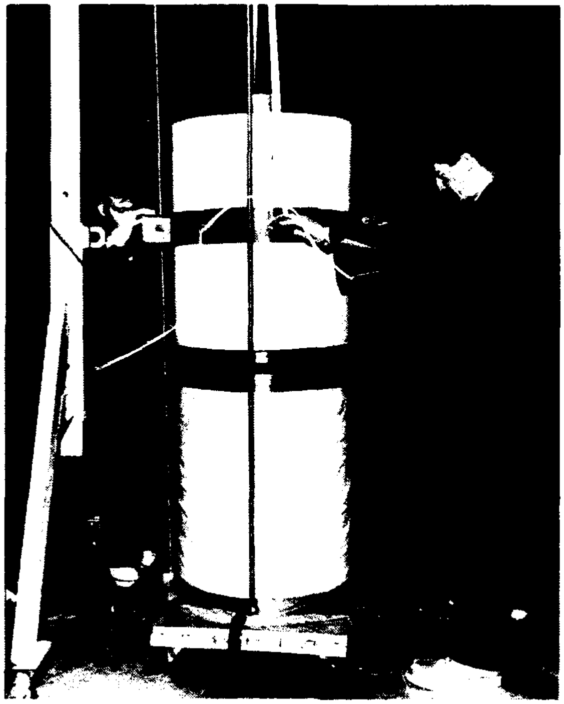


Figure 37. Joining of first and second bay of the cylindrical hull.

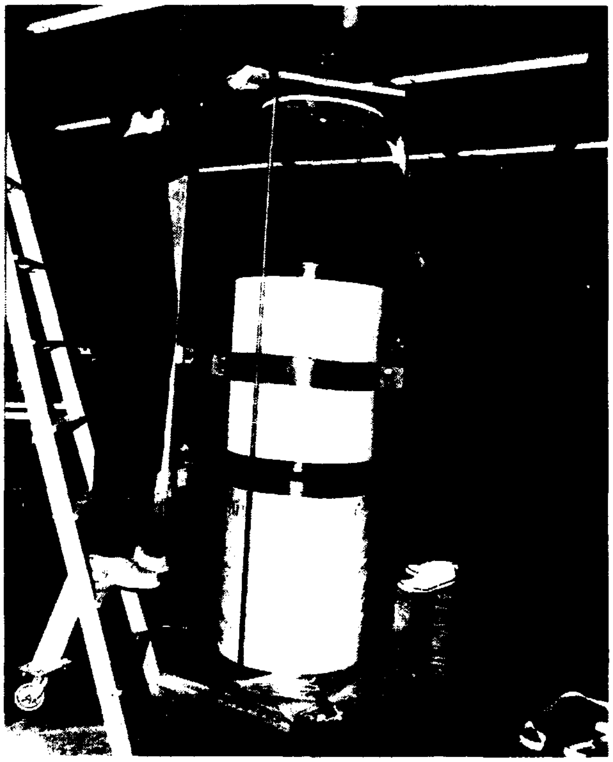


Figure 38. Clamping fixtures used for assembly of cylindrical hull.

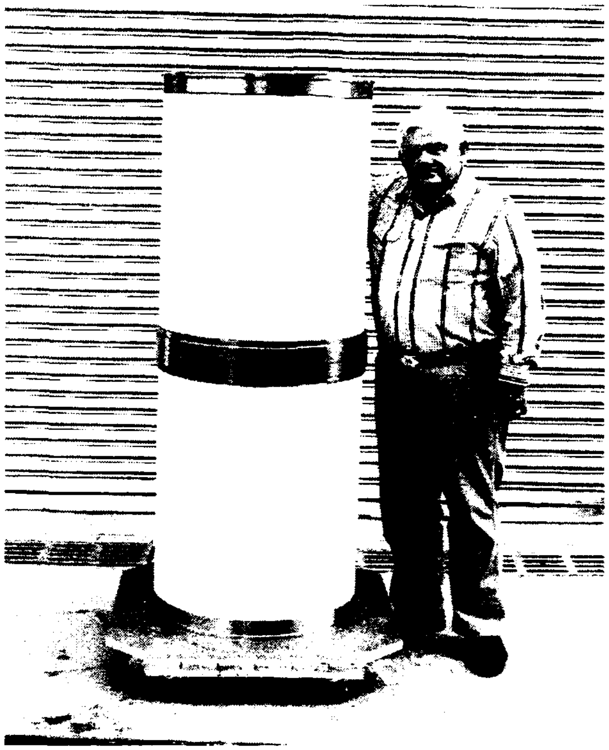


Figure 39. 26-inch-housing alumina-ceramic cylindrical hull.

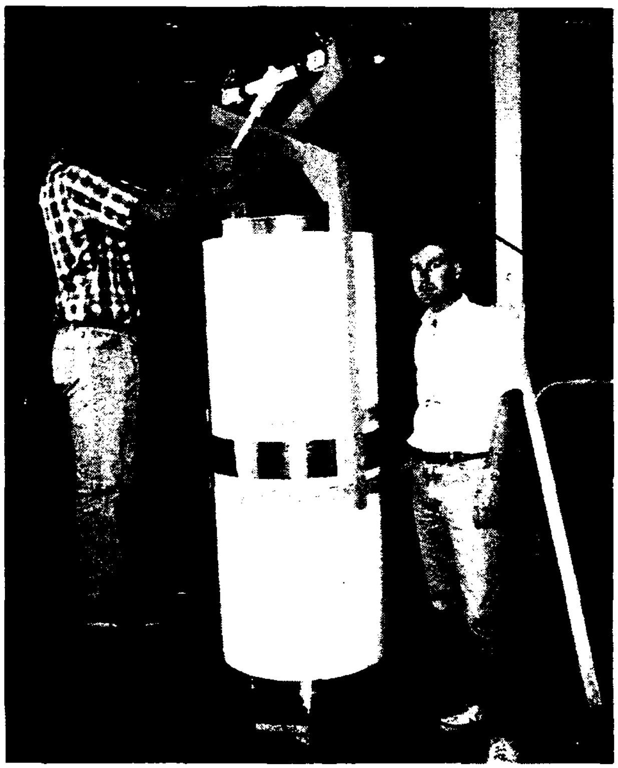


Figure 40. Handling of the cylindrical hull for placement into a horizontal position.

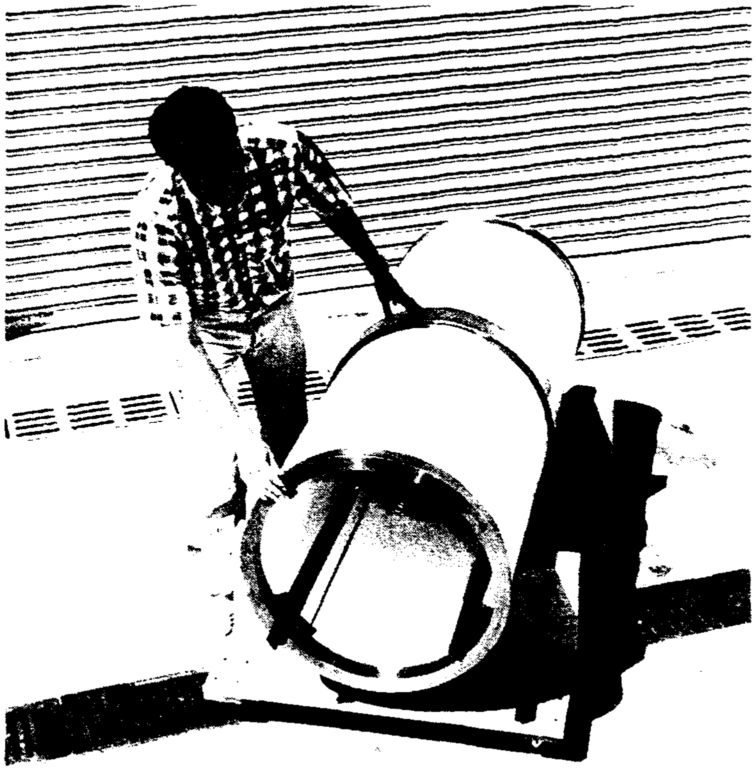


Figure 41. Cylindrical hull prior to attachment of composite fairings.

Figure 42. Attachment of external composite fairing to the cylindrical hull.

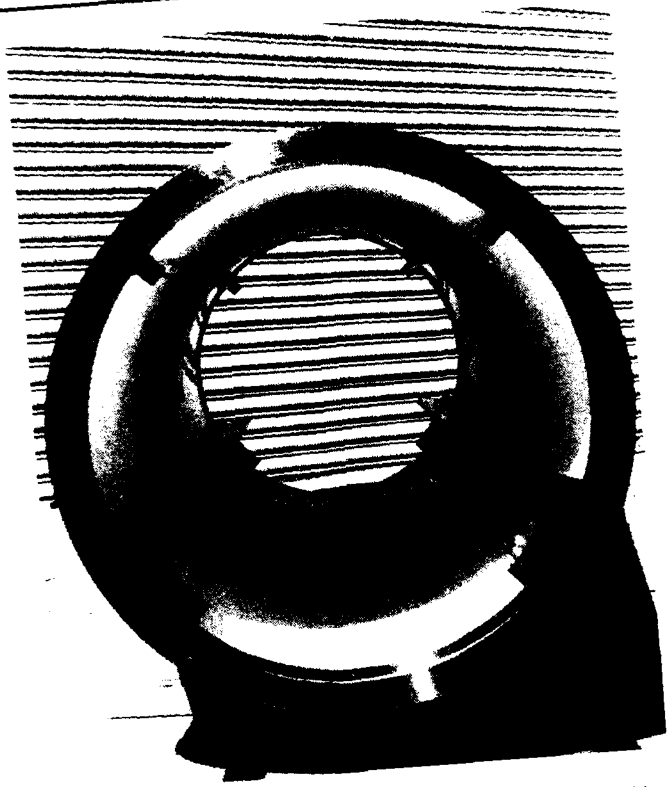


Figure 43. Internal view of 26-inch-housing cylindrical hull with payload rails and tie rods.

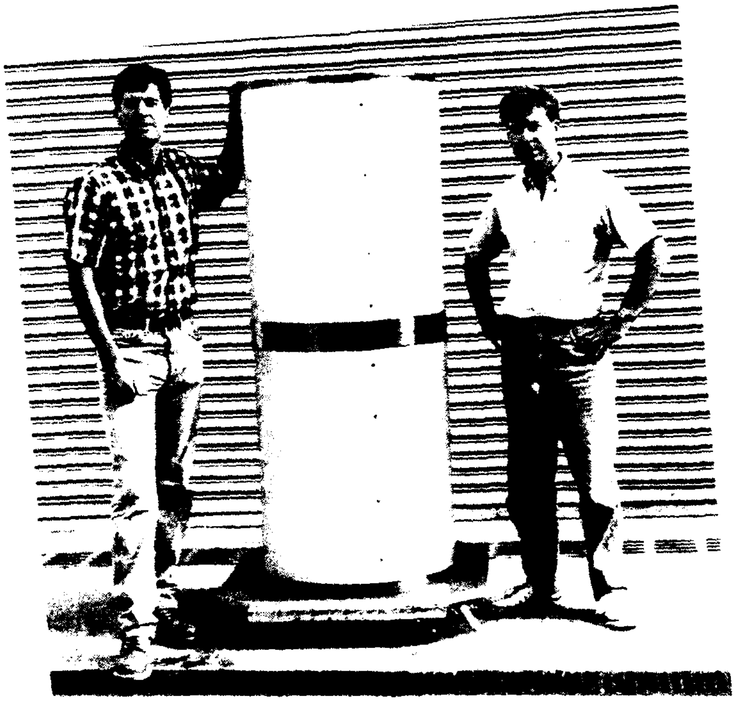
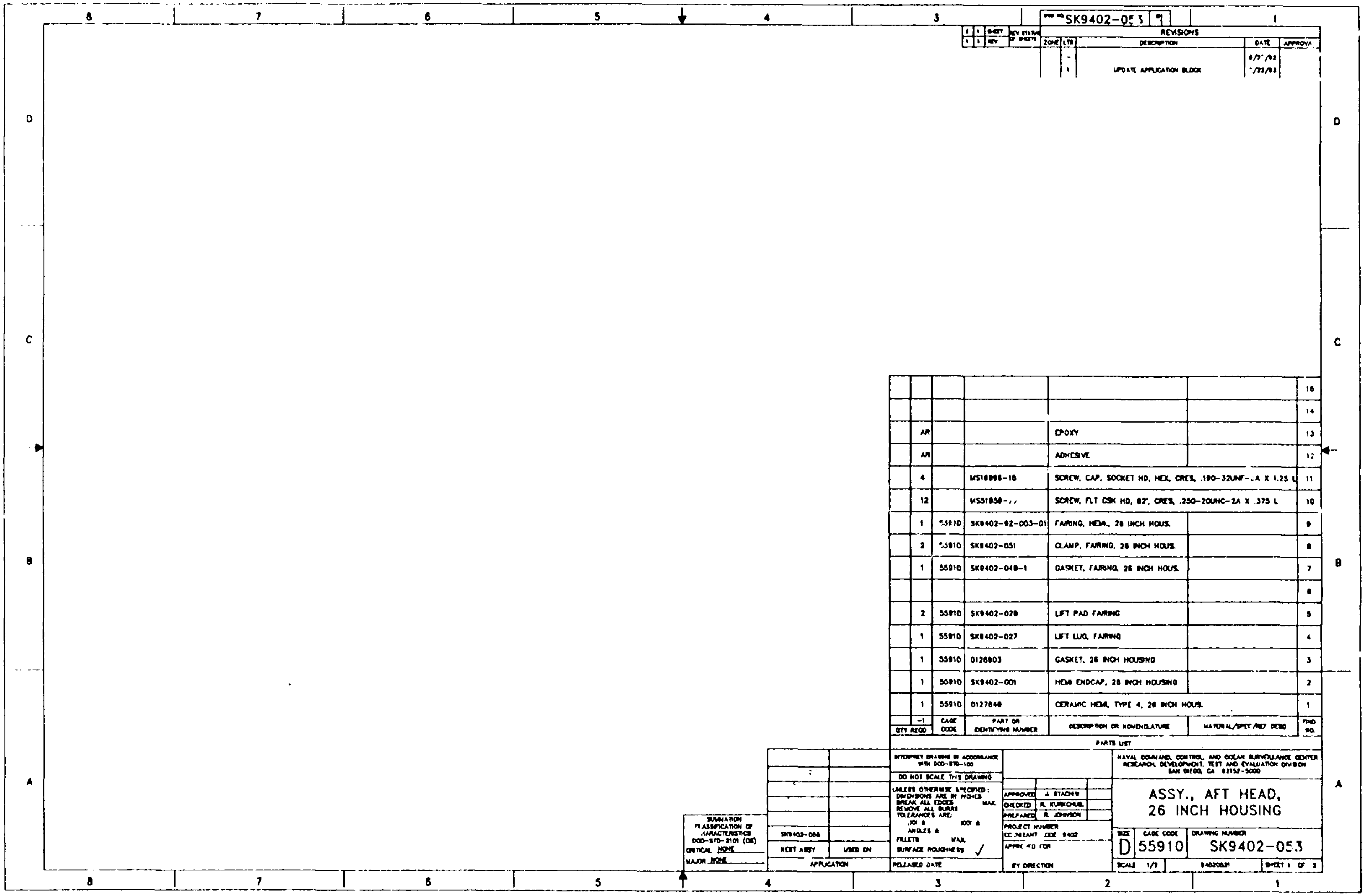


Figure 44. 26-inch-housing cylindrical hull with external composite fairing.

Figure 45. Packaging of 26-inch-housing cylindrical hull for shipment to pressure-testing facility at SRI.



QTY REQD	CAGE CODE	PART OR IDENTIFYING NUMBER	DESCRIPTION OR NOMENCLATURE	MATERIAL/SPEC/REF DESIG	FIND NO.
					15
					14
AR			EPOXY		13
AR			ADHESIVE		12
4		MS16996-16	SCREW, CAP, SOCKET HD, HEX, CRES, .190-32UNF-2A X 1.25 L		11
12		MS51958-//	SCREW, FLT CSK HD, 82°, CRES, .250-20UNC-2A X .375 L		10
1	55910	SK9402-92-003-01	FAIRING, HEM., 26 INCH HOUS.		9
2	55910	SK9402-051	CLAMP, FAIRING, 26 INCH HOUS.		8
1	55910	SK9402-049-1	GASKET, FAIRING, 26 INCH HOUS.		7
					6
2	55910	SK9402-028	LIFT PAD FAIRING		5
1	55910	SK9402-027	LIFT LUG, FAIRING		4
1	55910	0128803	GASKET, 26 INCH HOUSING		3
1	55910	SK9402-001	HEM ENDCAP, 26 INCH HOUSING		2
1	55910	0127840	CERAMIC HEM, TYPE 4, 26 INCH HOUS.		1

Figure 46. 26-inch-housing aft head assembly, sheet 1.

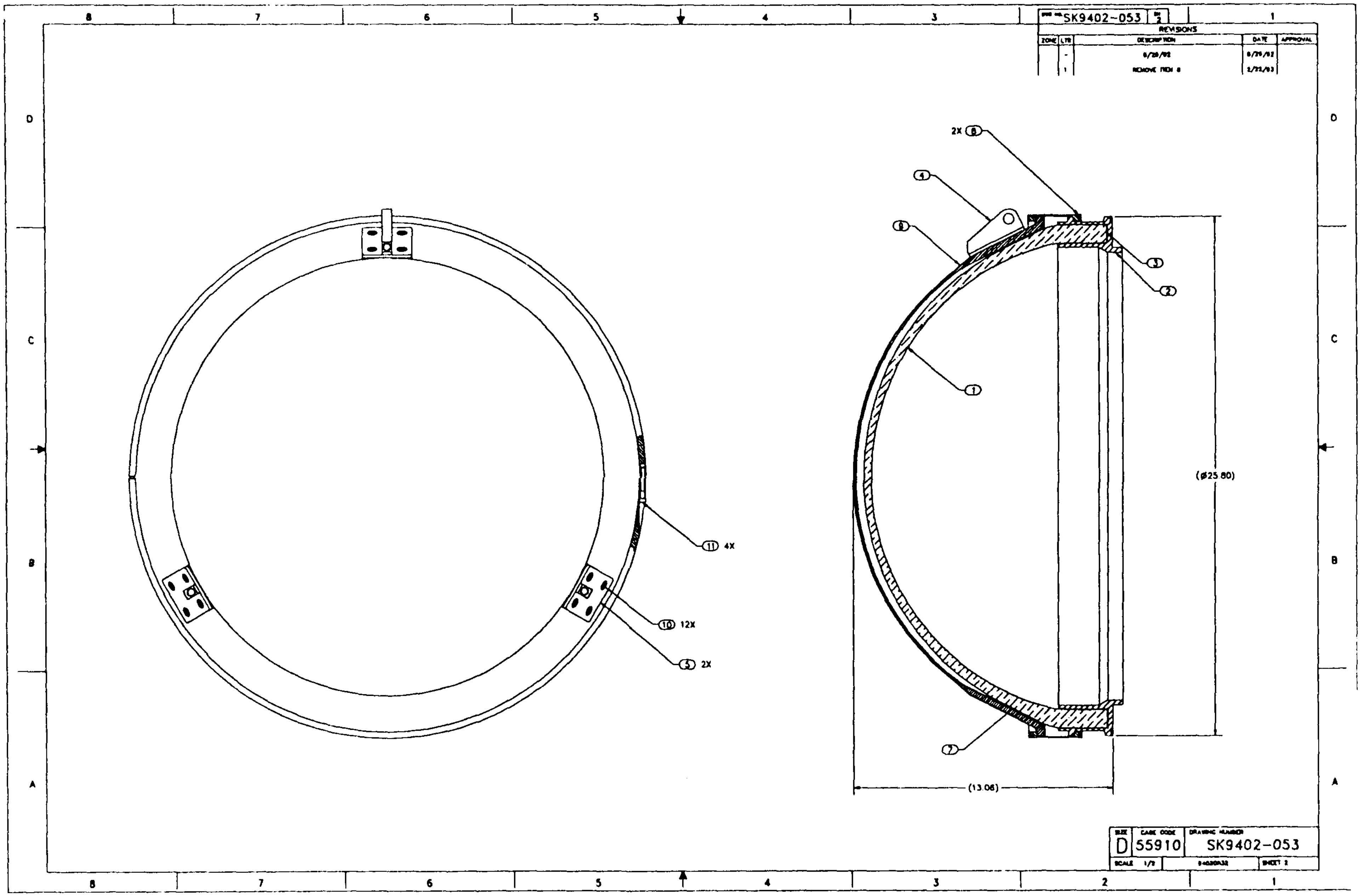


Figure 46. 26-inch-housing aft head assembly, sheet 2.

SK9402-052

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVAL
	–		5/25/93	
	1	REMOVE ITEM 14	2/22/93	

NOTES:

1. O-RINGS (ITEMS 18 AND 19) MAY BE PURCHASED FROM:

   PARKER SEAL GROUP
   O-RING DIVISION
   2360 PALUMBO DRIVE
   P.O. BOX 11751
   LEXINGTON, KY 40512
   (606) 269-2351

2. LUBRICATE O-RINGS (ITEMS 18 AND 19) WITH SILICONE COMPOUND (ITEM 24) PRIOR TO ASSEMBLY.

	QTY REQD -1	CAGE CODE	PART OR IDENTIFYING NUMBER	DESCRIPTION OR NOMENCLATURE	MATERIAL/SPEC/REF DESIG	FIND NO.
	AR			SILICONE COMPOUND	MIL-S-8660	24
	AR			EPOXY		23
	AR			ADHESIVE		22
	4		MS16996-15	SCREW, CAP, SOCKET HD, HEX, CRES, .190-32UNF-3A X 1.25 L		21
	12		MS51959-77	SCREW, FLT CSK HD, 82°, CRES, .250-20UNC-2A X .375 L		20
	4		2-228	O-RING	⚠	19
	2		2-214	O-RING	⚠	18
	1	55910	SK9402-92-003-01	FAIRING, HEM., 26 INCH HOUS.		17
	2	55910	SK9402-051	CLAMP, FAIRING, 26 INCH HOUS.		16
	1	55910	SK9402-049-1	GASKET, FAIRING, 26 INCH HOUS.		15
						14
	4	55910	SK9402-031-4	WASHER, PENETRATION, ELEC. FEED		13
	4	55910	SK9402-031-3	SPACER, PENETRATION, ELEC. FEED.		12
	4	55910	SK9402-031-2	NUT, PENETRATION, ELEC. FEED.		11
	4	55910	SK9402-031-1	PENETRATION, ELEC. FEEDTHRU		10
	2	55910	SK9402-030-4	WASHER, PENETRATION, PRES. REL.		9
	2	55910	SK9402-030-3	SPACER, PENETRATION, PRES. REL.		8
	2	55910	SK9402-030-2	NUT, PENETRATION, PRES. RELIEF		7
	2	55910	SK9402-030-1	PENETRATION, PRESSURE RELIEF		6
	2	55910	SK9402-029	LIFT PAD FAIRING		5
	1	55910	SK9402-027	LIFT LUG, FAIRING		4
	1	55910	0129903	GASKET, 26 INCH HOUSING		3
	1	55910	SK9402-001	HEMI ENDCAP, 26 INCH HOUSING		2
	1	55910	012775	CERAMIC HEMI, TYPE 8, 26 INCH HOUS.		1

PARTS LIST

INTERPRET DRAWING IN ACCORDANCE WITH DOD-STD-100

DO NOT SCALE THIS DRAWING

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES. BREAK ALL EDGES. REMOVE ALL BURRS. TOLERANCES ARE .XX ± .XXX ± ANGLES ± FILLETS MAX. SURFACE ROUGHNESS √

APPROVED J. STACHIV
CHECKED R. KURKCHUBASCHE
PREPARED R. JOHNSON

NAVAL COMMAND, CONTROL, AND OCEAN SURVEILLANCE CENTER
RESEARCH, DEVELOPMENT, TEST AND EVALUATION DIVISION
SAN DIEGO, CA 92152-5000

ASSY., FORWARD HEAD, 26 INCH HOUSING

SIZE D | CAGE CODE 55910 | DRAWING NUMBER SK9402-052

SCALE 1/8 | SHEET 1 OF 8

NEXT ASSY SK9402-050 | USED ON | APPLICATION

SEAMATION CLASSIFICATION OF CHARACTERISTICS DOD-STD-2101 (OS)
CRITICAL NONE
MAJOR NONE

Figure 47. 26-inch-housing forward head assembly, sheet 1.

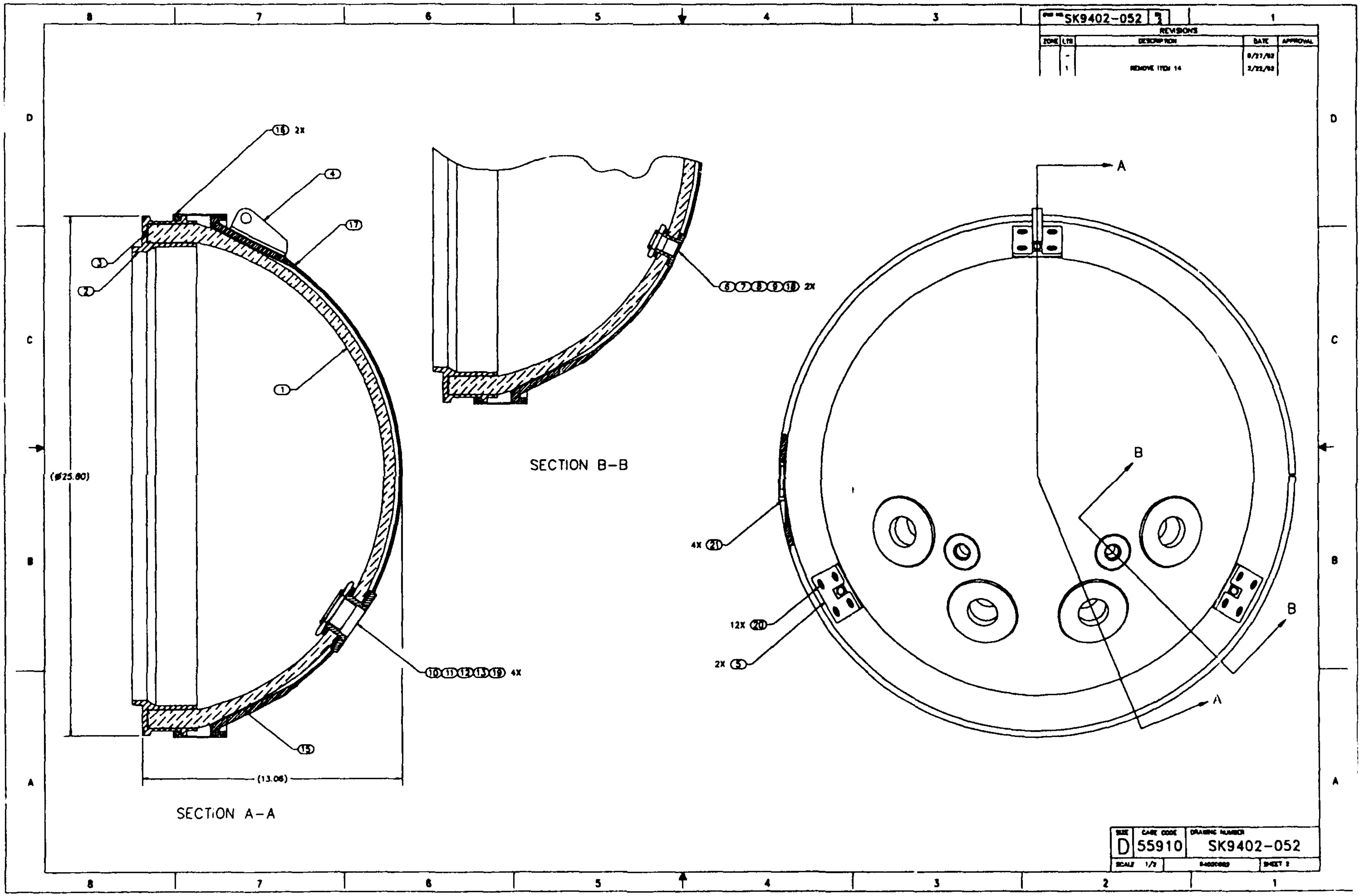


Figure 47. 26-inch-housing forward head assembly, sheet 2.

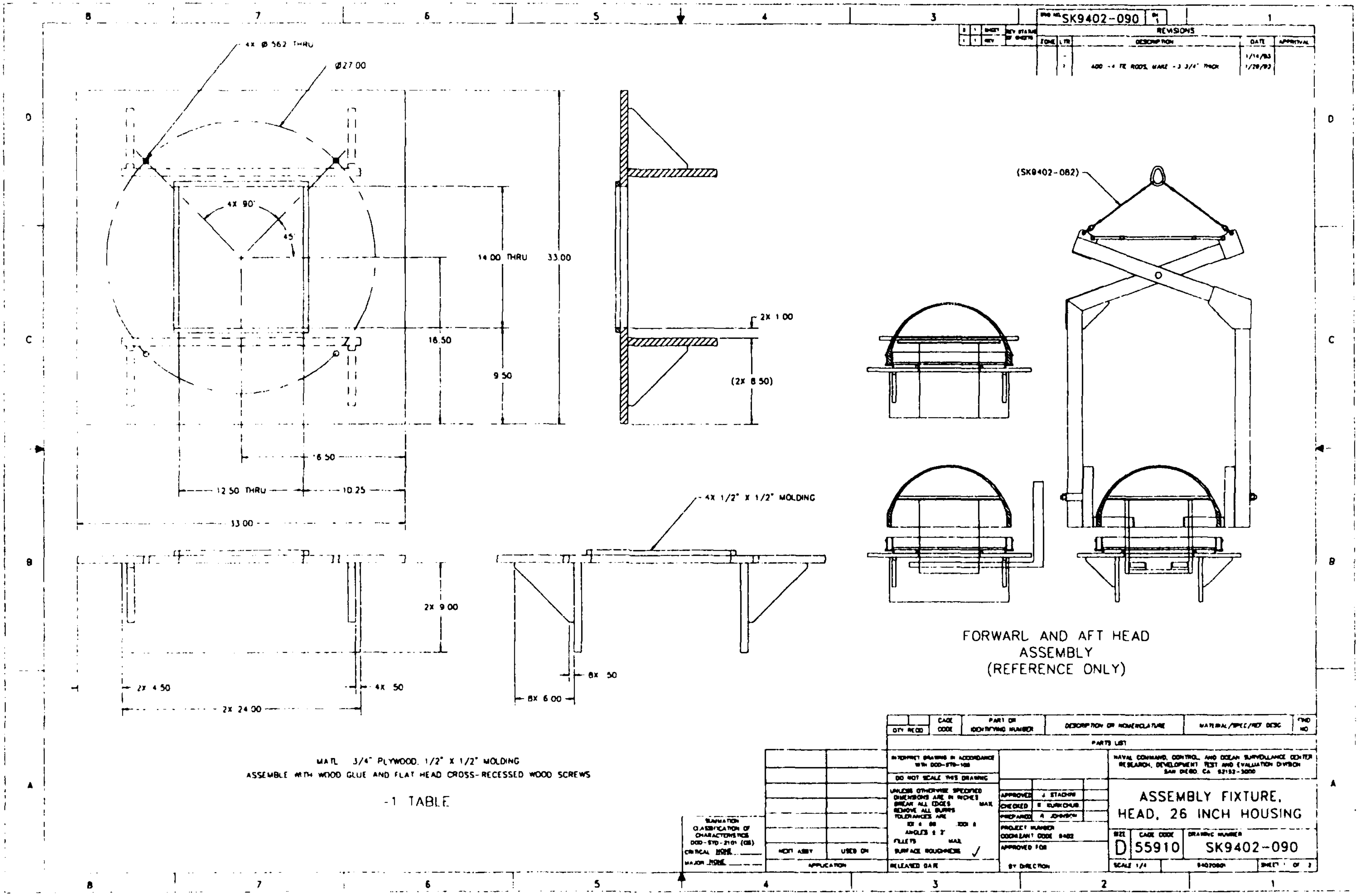


Figure 48. 26-inch-housing aft and forward head assembly fixtures, sheet 1.

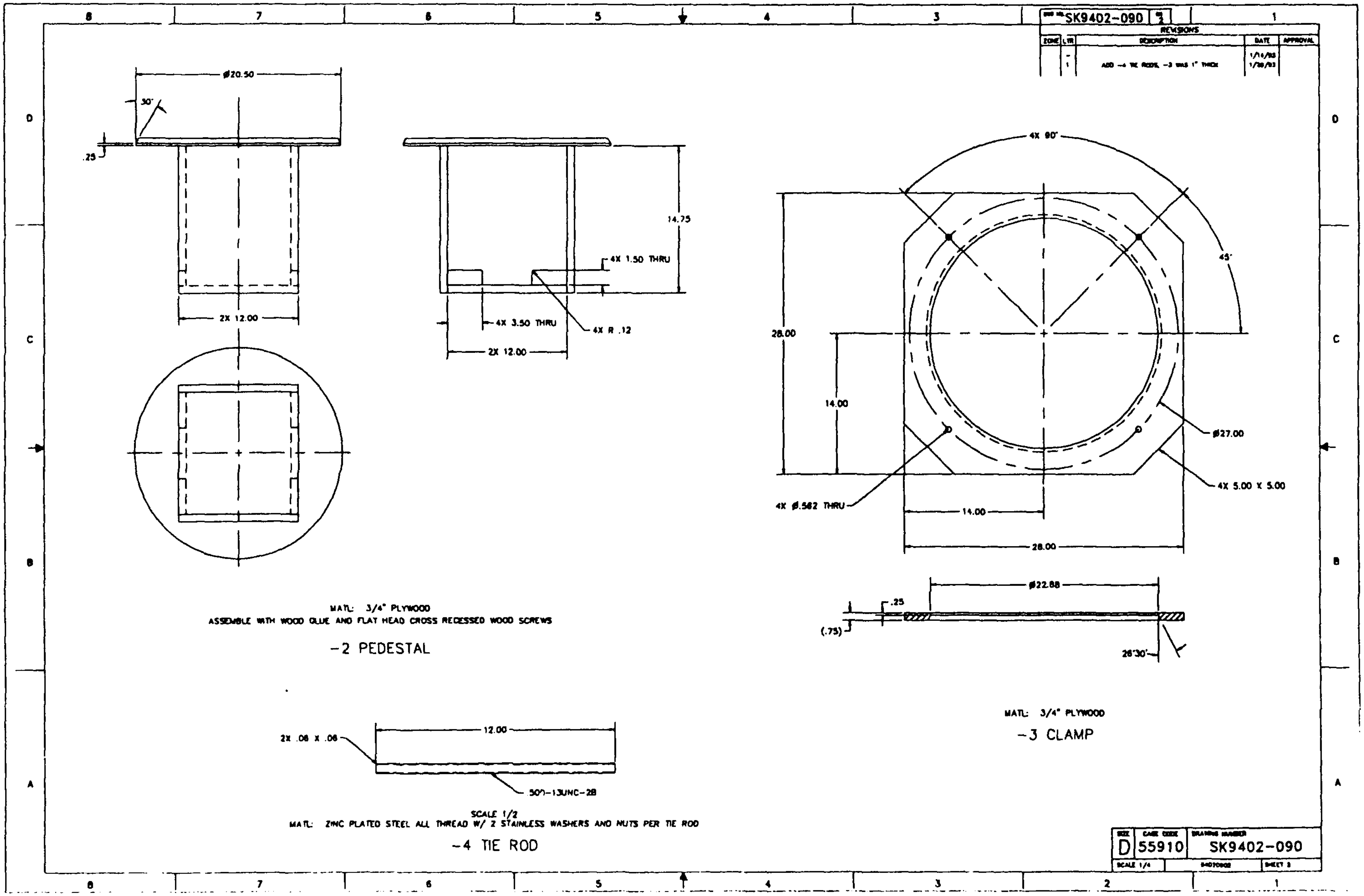


Figure 48. 26-inch-housing aft and forward head assembly fixtures, sheet 2.

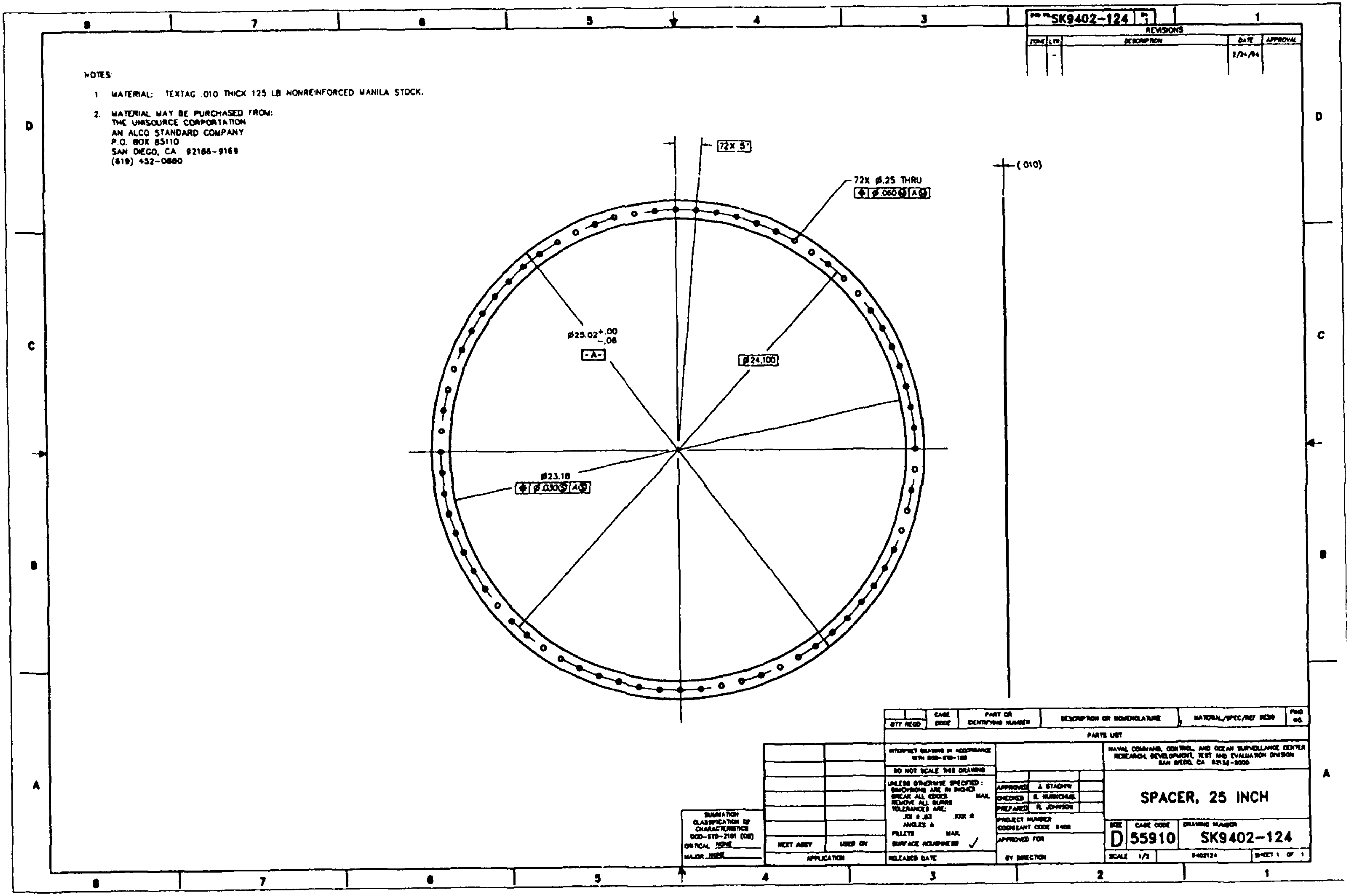


Figure 49. Engineering drawing of the axial bearing-surface spacer for the forward and aft heads.

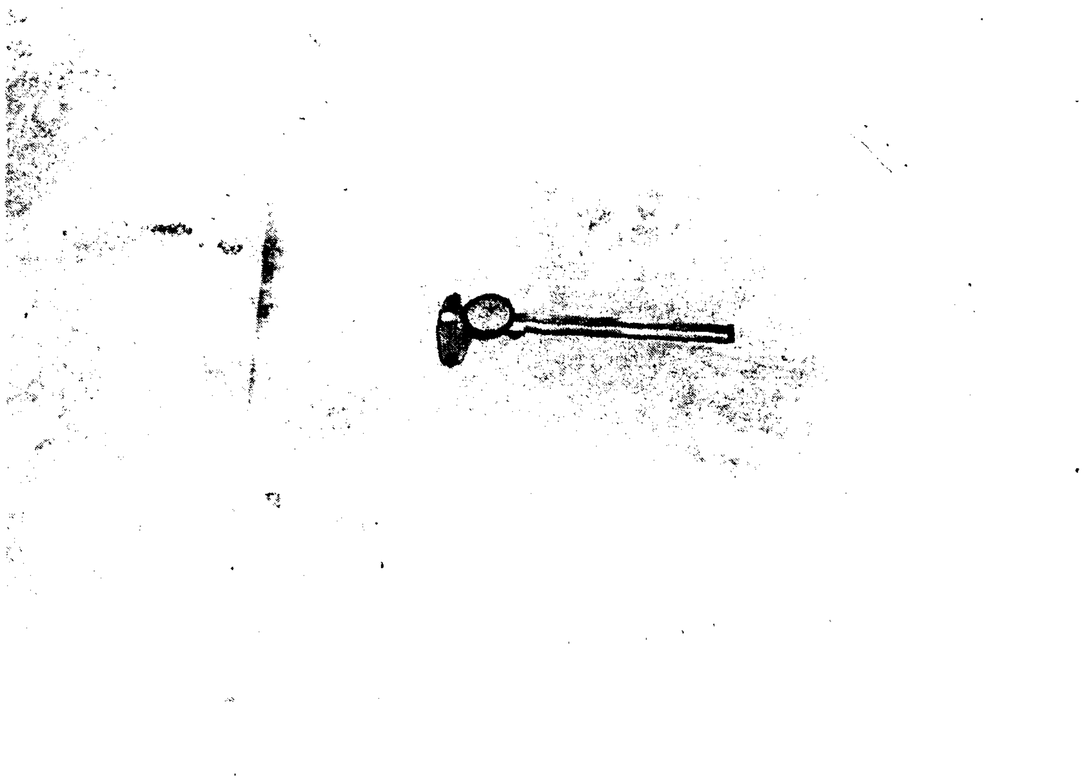


Figure 50. Axial bearing-surface spacer for forward and aft heads.

Figure 51. Type 4 alumina hemisphere used in aft head assembly.

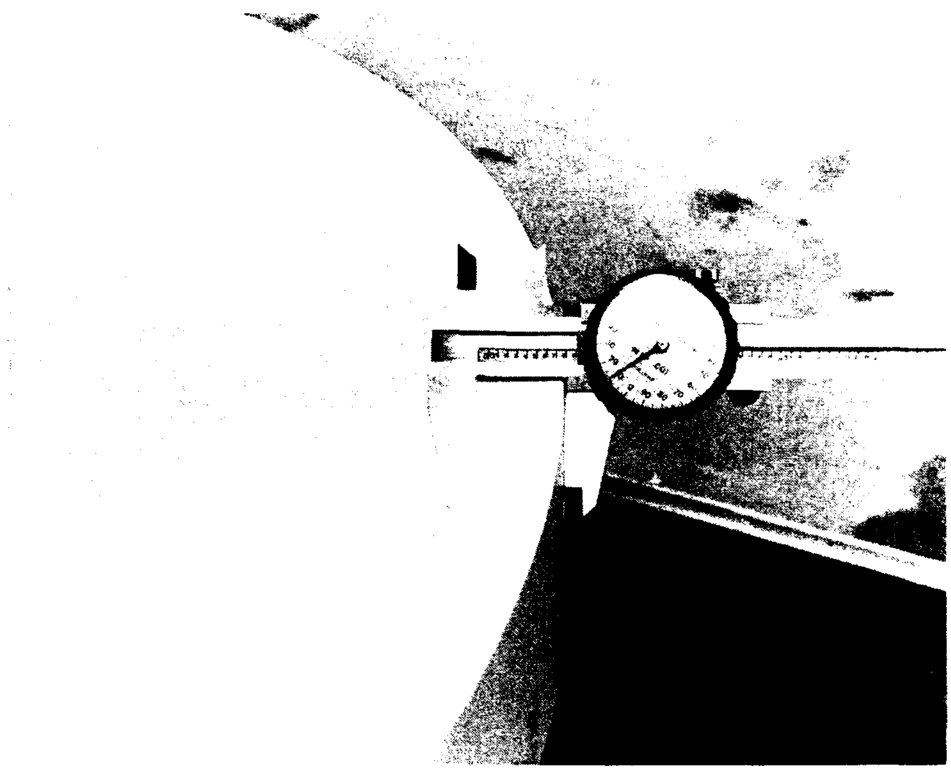


Figure 52. Axial bearing-surface Type 4 alumina hemisphere.

Figure 53. Placement of axial bearing-surface spacer in titanium end-cap joint ring.

Figure 54. Assembly of aft head alumina hemisphere with titanium end-cap joint ring.

Figure 55. Assembly fixture for forward and aft heads.

Figure 56. 26-inch-housing aft head without protective external fairing.

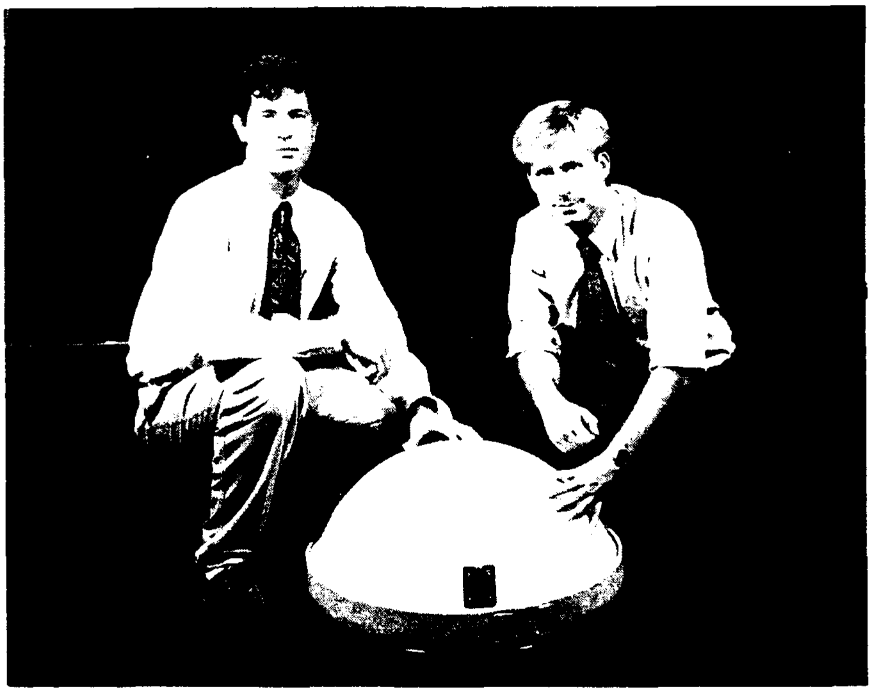


Figure 57. 26-inch-housing aft head with protective external fairing.

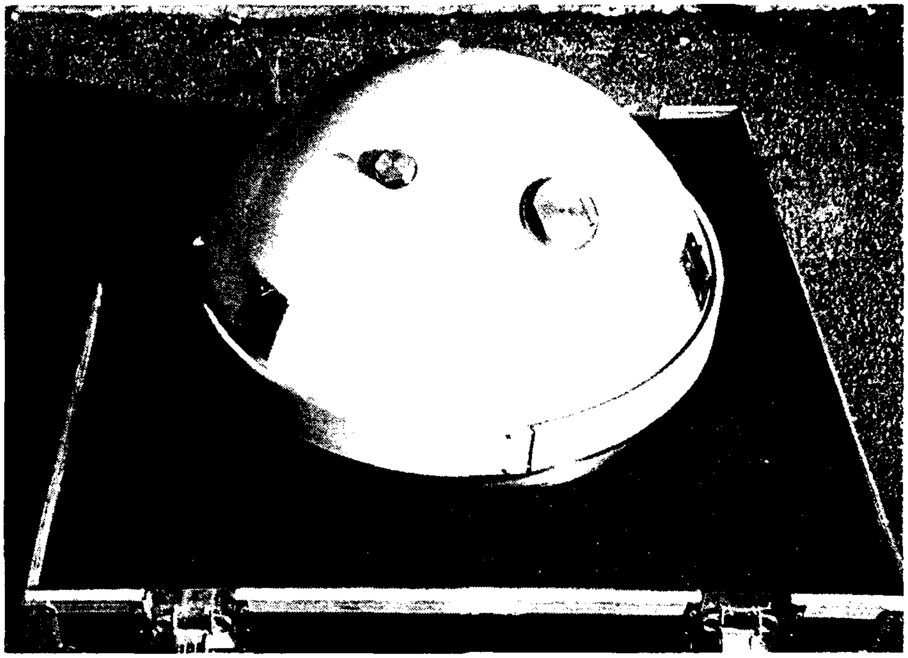


Figure 58. External view of 26-inch-housing forward head with protective external fairing.

Figure 59. External view of 26-inch-housing forward head with protective external fairing

Figure 60. Internal view of 26-inch-housing forward head.

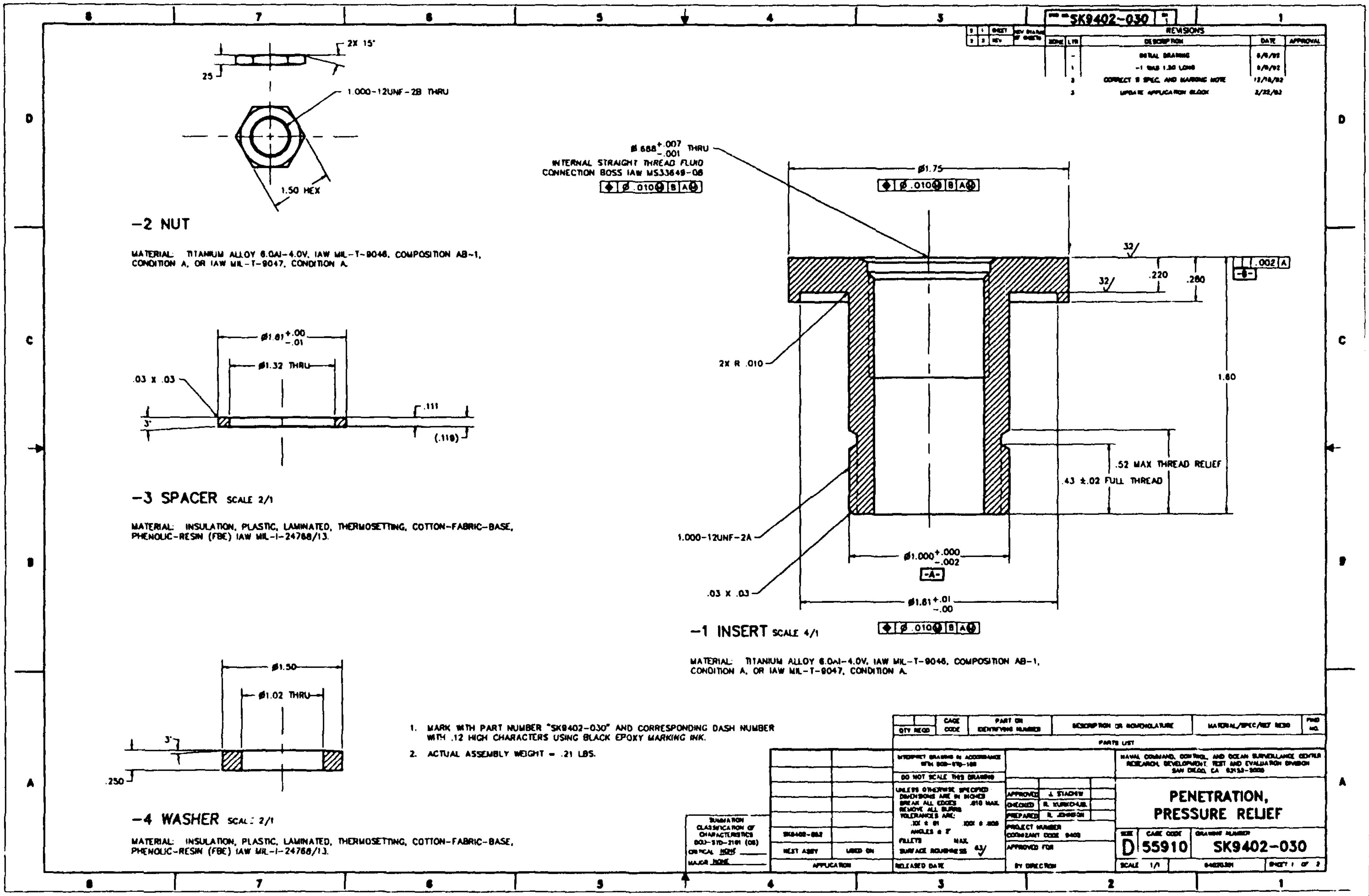


Figure 61. Original design of the pres.:ure-relief insert for the forward head assembly, sheet 1.

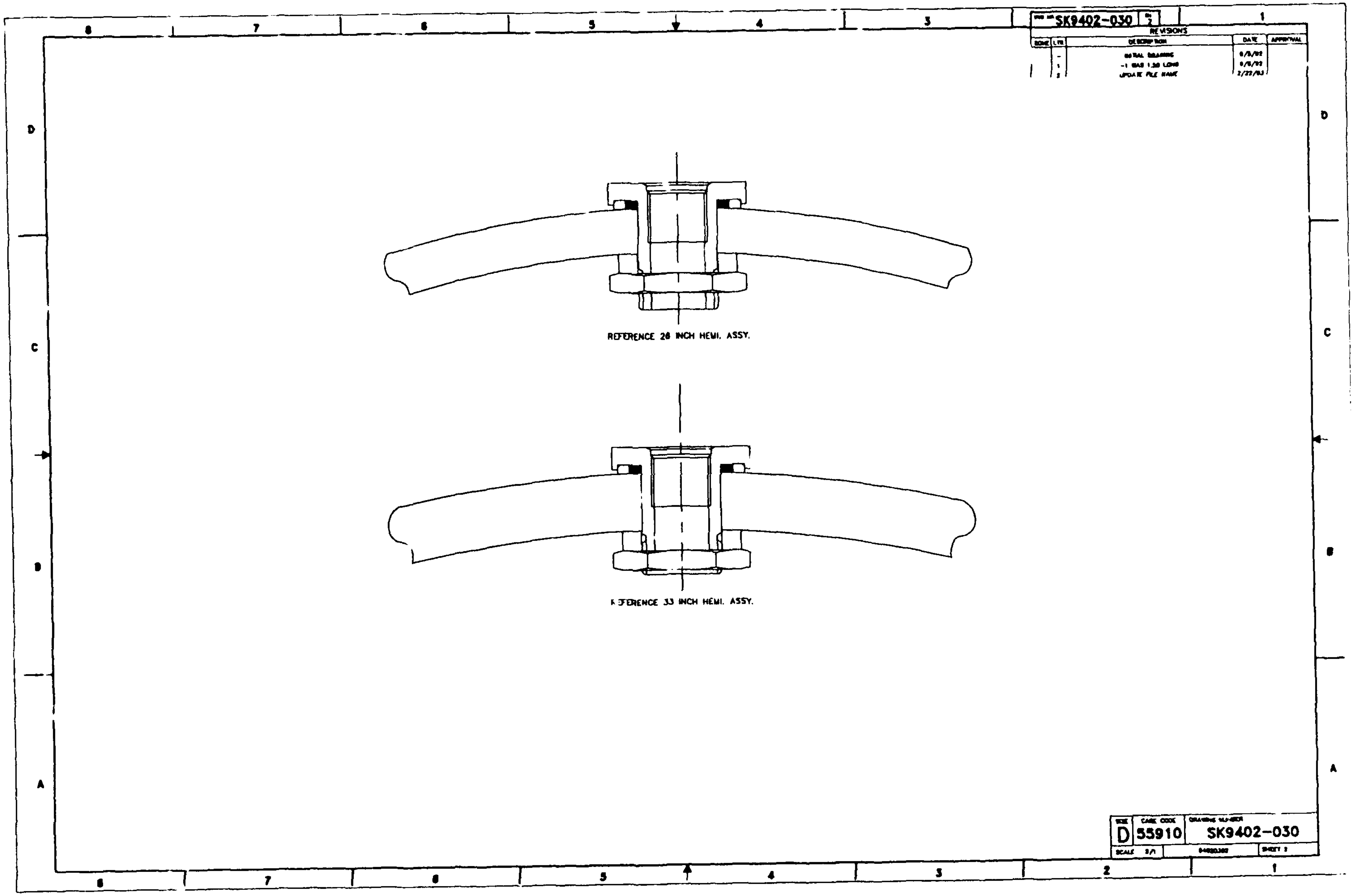


Figure 61. Original design of the pressure-relief insert for the forward head assembly, sheet 2.

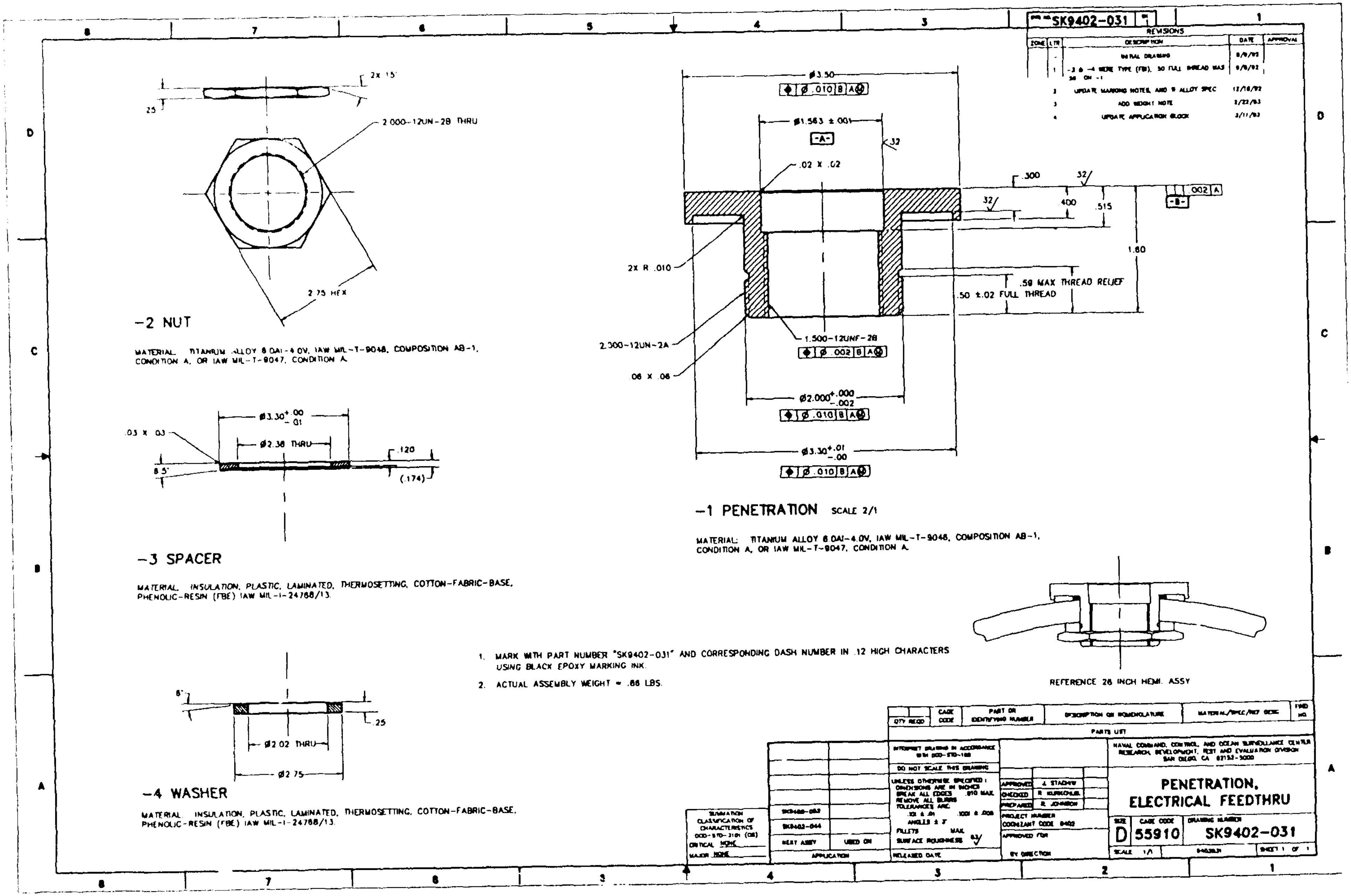


Figure 62. Original design of the electrical-connector insert for the forward head assembly.

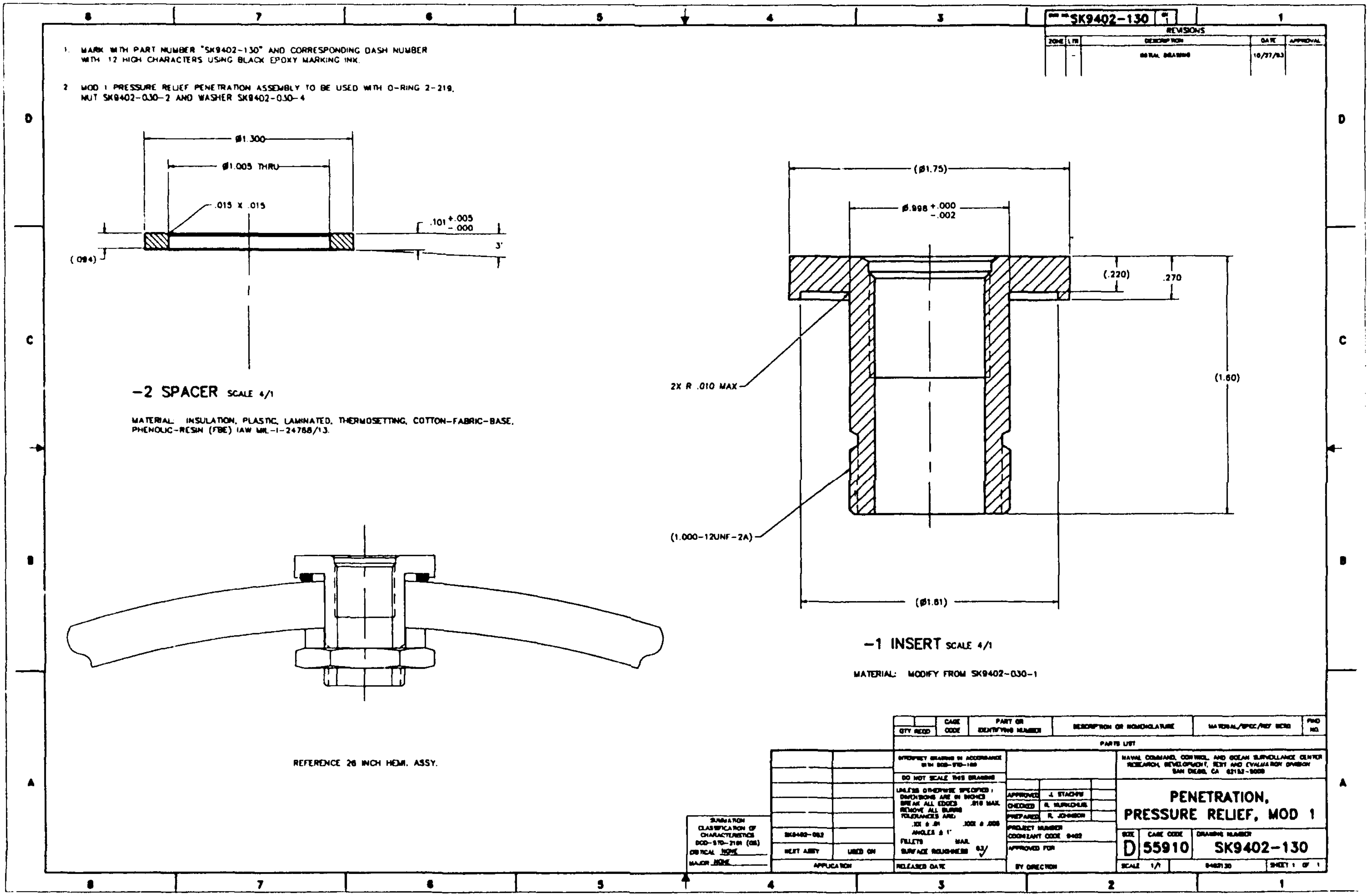


Figure 63. Modified design of the pressure-relief insert for the forward head assembly.

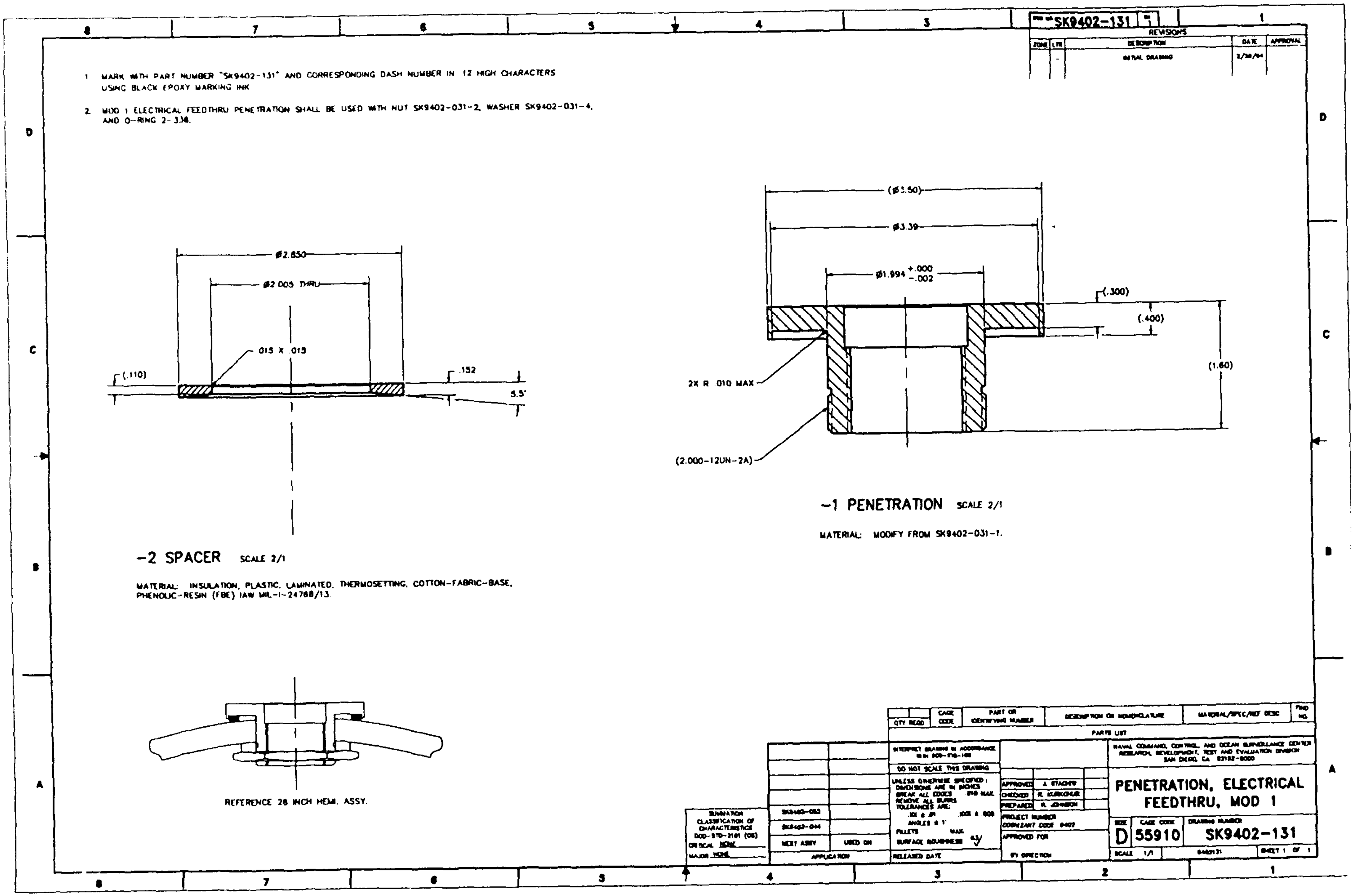


Figure 64. Modified design of the electrical connector insert for the forward head assembly.

SK9402-102

NOTES:

1. LUBRICATE O-RINGS (ITEM 2, 11 & 12) WITH SILICONE COMPOUND (ITEM 13) PRIOR TO ASSEMBLY.

2. PROOF TESTING OF THE 26 INCH HOUSING HULL SECTION (ITEM 3) SHALL BE PERFORMED AS OUTLINED IN NOTE 4 PRIOR TO PRESSURE TESTING THE COMPLETE 26 INCH HOUSING ASSEMBLY (SK9402-055).

3. ALL ELECTRIC RESISTANCE STRAIN GAUGES ARE 90° RECTANGULAR ROSETTES. ALL STRAIN GAUGES SHALL BE MOUNTED WITH ONE LEG ORIENTATED IN THE HOOP DIRECTION. ALL GAUGES TO BE WATERPROOFED. GAUGE SIZE SHALL BE 1/8.

4. PRESSURE TESTING SHALL BE PERFORMED IN TAP WATER AT AMBIENT ROOM TEMPERATURE AND SHALL CONSIST OF AT A MINIMUM THE FOLLOWING TESTS.

   A. PRESSURIZE TO 10,000 PSI AT AN APPROXIMATE RATE OF 1000 PSI PER MINUTE READING THE STRAINS AT 1000 PSI INTERVALS. AFTER 60 MINUTES AT A SUSTAINED PRESSURE OF 10,000 PSI RECORD ALL STRAINS AND DEPRESSURIZE TO 0 PSI AT AN APPROXIMATE RATE OF 10,000 PSI PER MINUTE. AFTER DEPRESSURIZATION RECORD ALL RESIDUAL STRAINS.

   B. PRESSURE CYCLE FROM 50 TO 9000 PSI TEN TIMES, HOLDING AT 9000 PSI FOR ONE MINUTE DURING EACH CYCLE. REMOVE HOUSING AND DISASSEMBLE FOR INSPECTION.

5. PRESSURE TEST DOCUMENTATION SHALL CONSIST OF THE FOLLOWING:

   A. PHOTOGRAPHS OF THE TEST CONFIGURATION AFTER ASSEMBLY AND AS IT IS LOADED INTO PRESSURE VESSEL USING 26 INCH HOUSING TEST FIXTURE (ITEM 7).

   B. COMPUTER PRINTOUT OF ALL STRAINS RECORDED FOR INITIAL PROOF TEST TO 10,000 PSI.

   C. STRIP CHARTS WITH PRESSURE HISTORIES FOR EACH PRESSURIZATION.

QTY REQD (-1)	CAGE CODE	PART OR IDENTIFYING NUMBER	DESCRIPTION OR NOMENCLATURE	MATERIAL/SPEC/REF DESIG	FIND NO.
AR			SILICONE COMPOUND	MIL-S-8660	13
2		2-226	O-RING		12
2		2-219	O-RING		11
6		MS16998-16	SCREW, CAP, SOCKET HD, HEX, CRES, 190-32UNF-3A X 1.5L		10
					9
2	55910	0128998	TEST HEMISPHERE, 26 INCH HOUSING		8
1	55910	SK9402-065	TEST FIXTURE, 26 INCH HOUSING		7
1	55910	SK9402-038	ELECTRICAL FEEDTHRU		6
1	55910	SK9402-074-2	PLUG, PENETRATION, ELECTRICAL FEEDTHRU		5
					4
1	55910	SK9402-054	HULL, 26 INCH HOUSING		3
2	55910	SK9402-033	O-RING, 26 INCH HOUSING		2
4	55910	SK9402-003	CLAMP BAND, 26 INCH HOUSING		1

PARTS LIST

NAVAL COMMAND, CONTROL, AND OCEAN SURVEILLANCE CENTER
RESEARCH, DEVELOPMENT, TEST AND EVALUATION DIVISION
SAN DIEGO, CA 92152-5000

TEST CONFIGURATION, HULL, 26 INCH HOUSING

SIZE D | CAGE CODE 55910 | DRAWING NUMBER SK9402-102 | SCALE NONE | SHEET 1 OF 2

APPROVED J. STACHIW | CHECKED R. KURKCHUBASCHE | PREPARED R. JOHNSON

Figure 65. 26-inch-housing cylindrical hull test configuration, sheet 1.

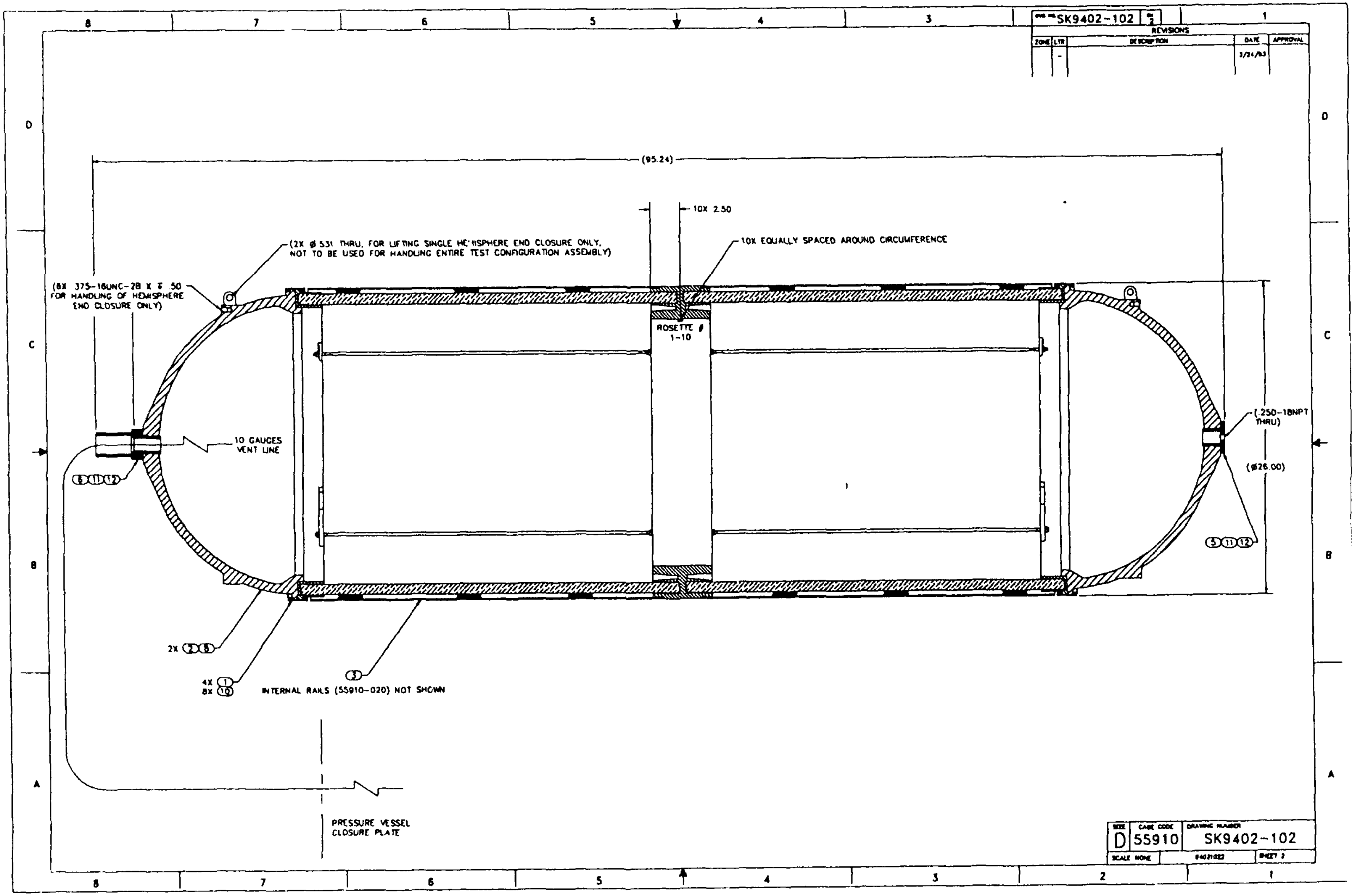


Figure 65. 26-inch-housing cylindrical hull test configuration, sheet 2.

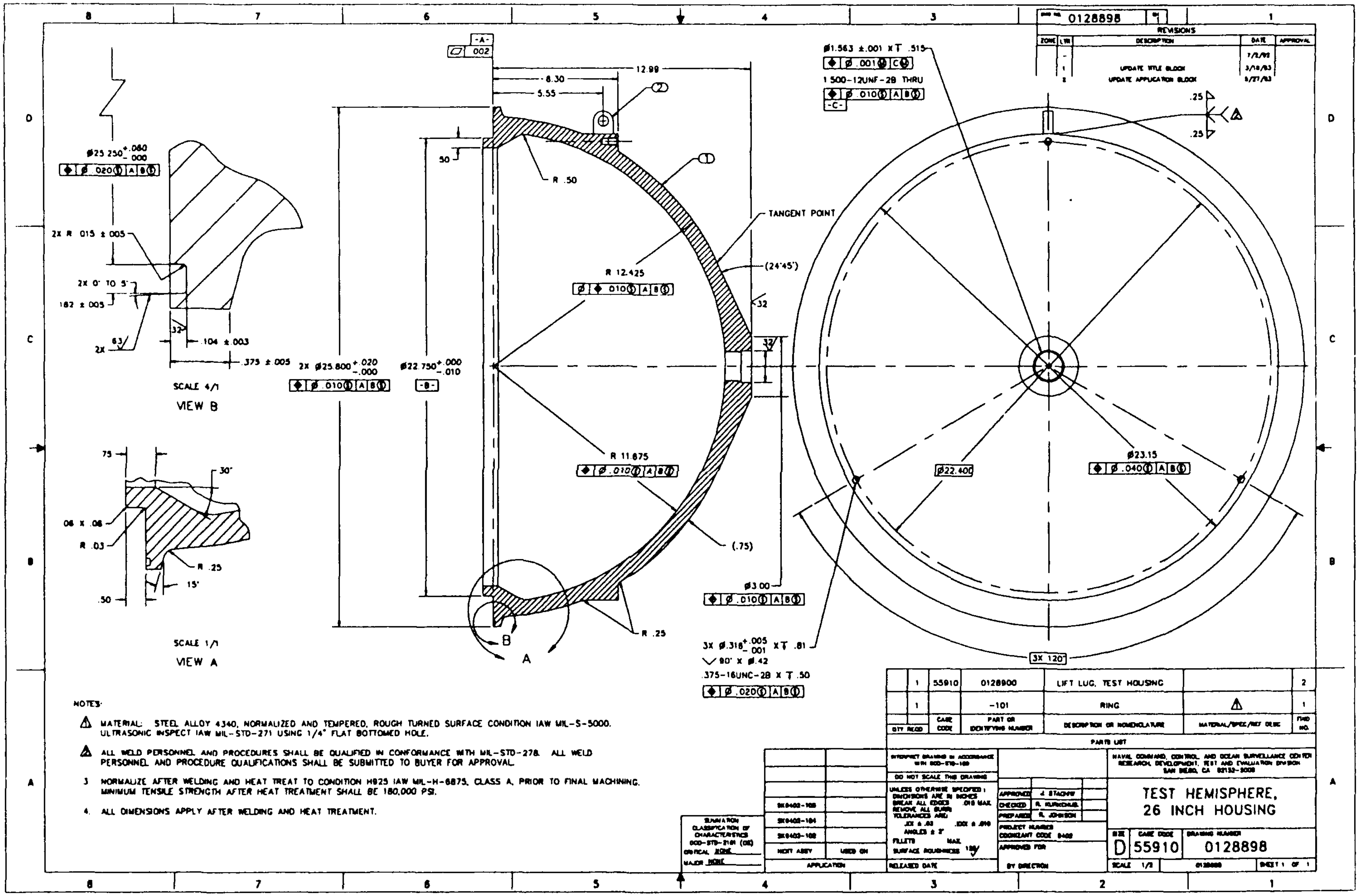


Figure 66. 26-inch-housing steel test hemisphere.

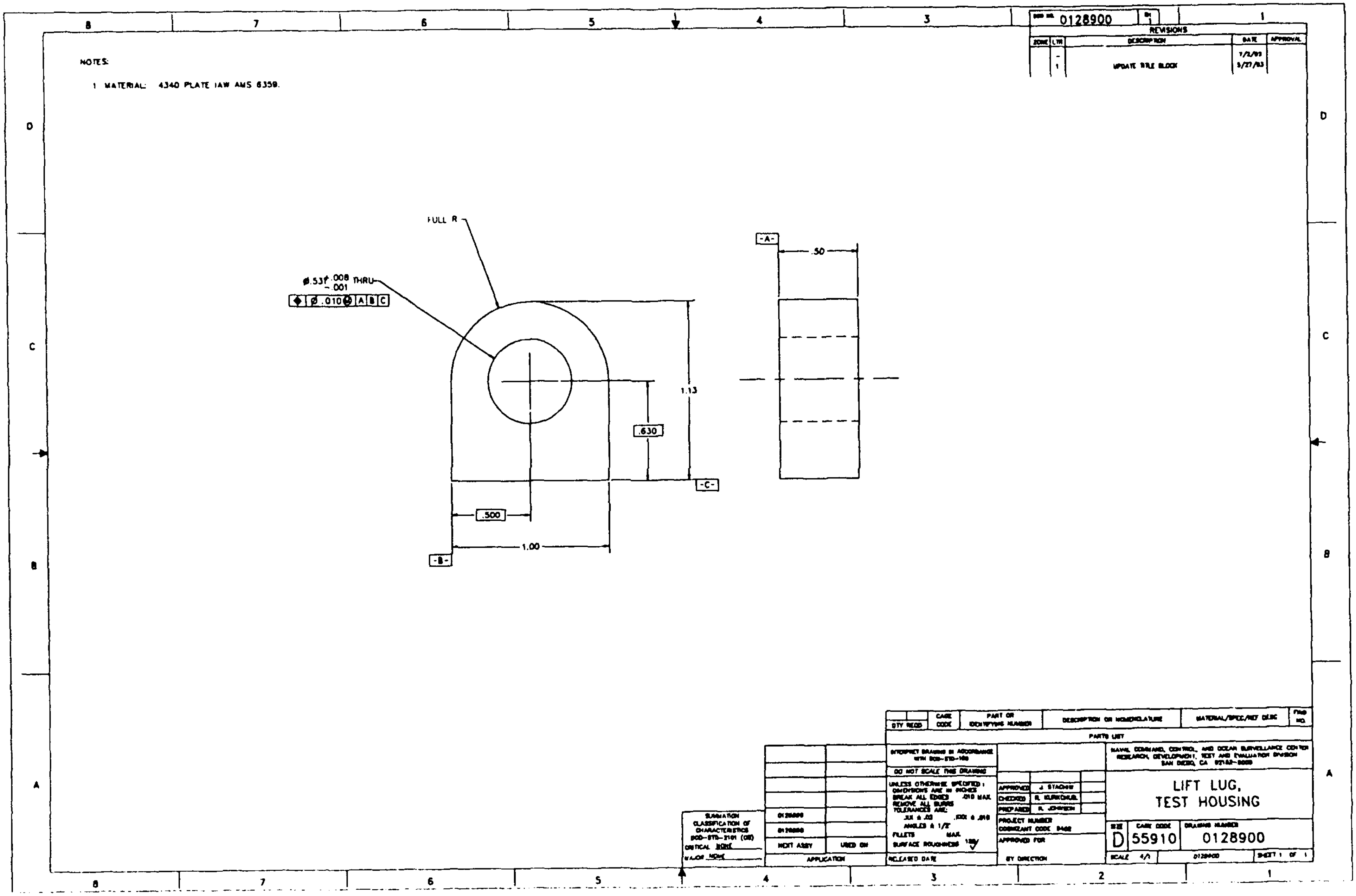


Figure 67. Test housing lift lug.

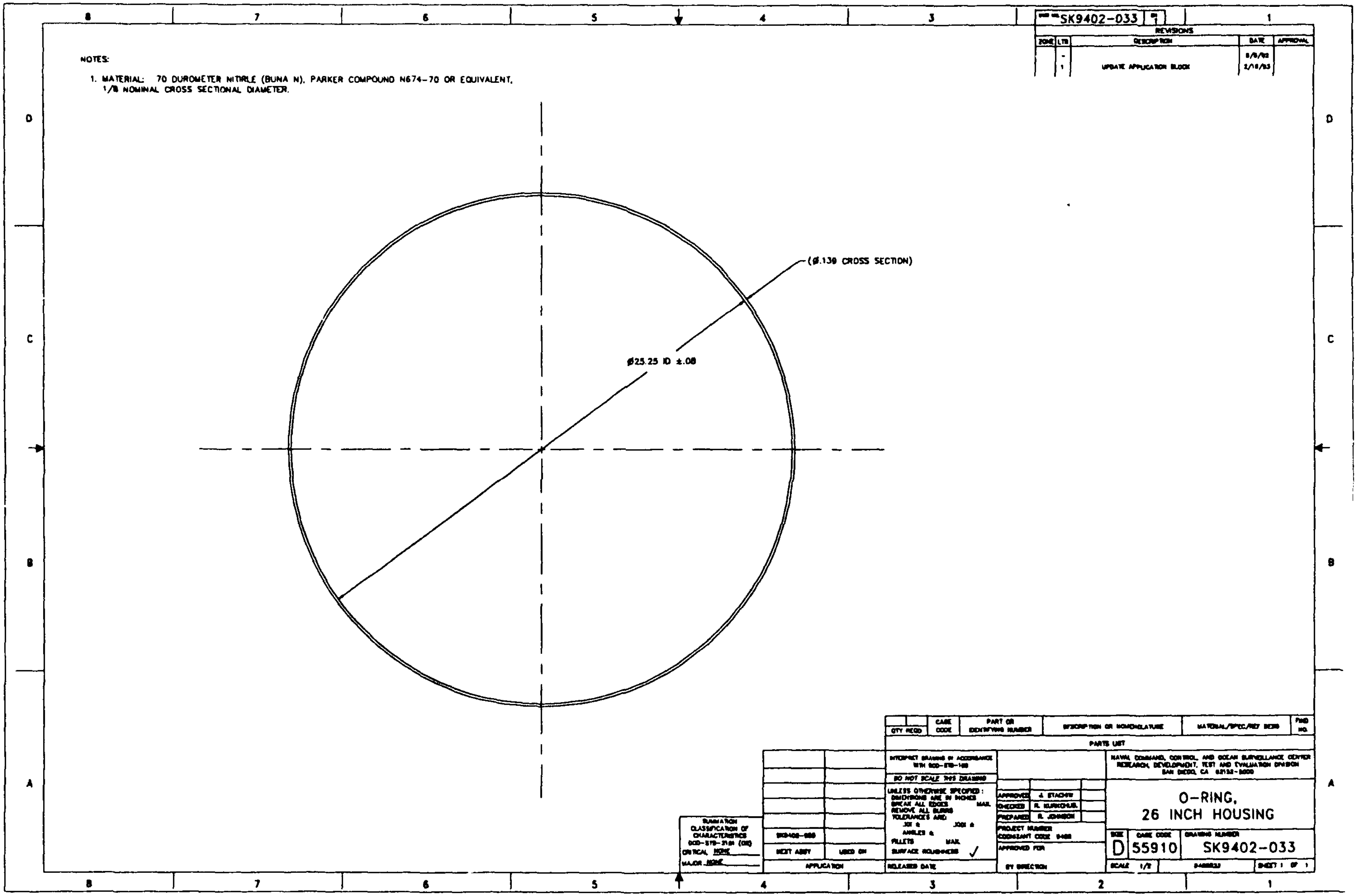


Figure 68. 26-inch-housing O-ring.

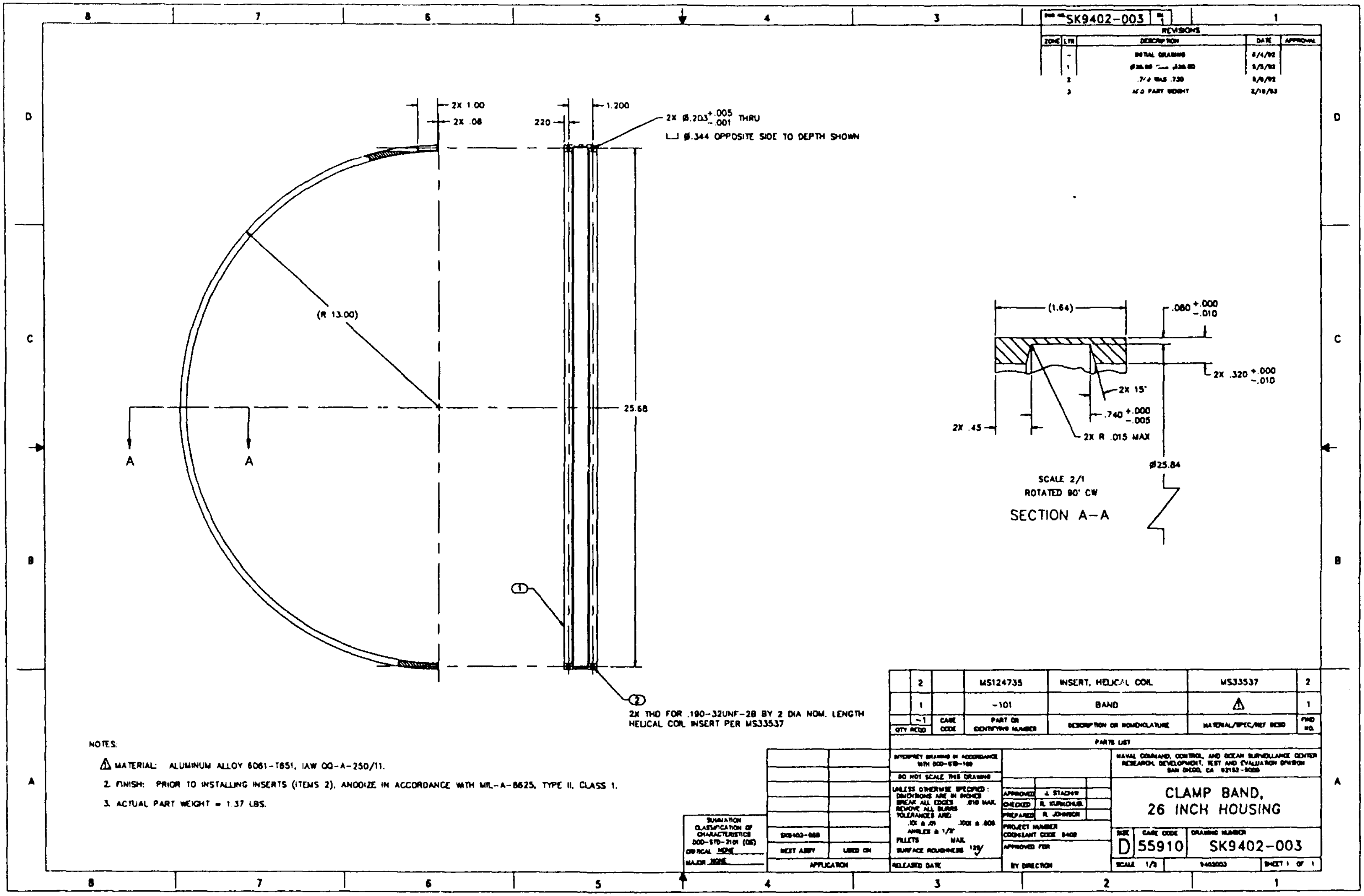


Figure 69. 26-inch-housing clamp band.

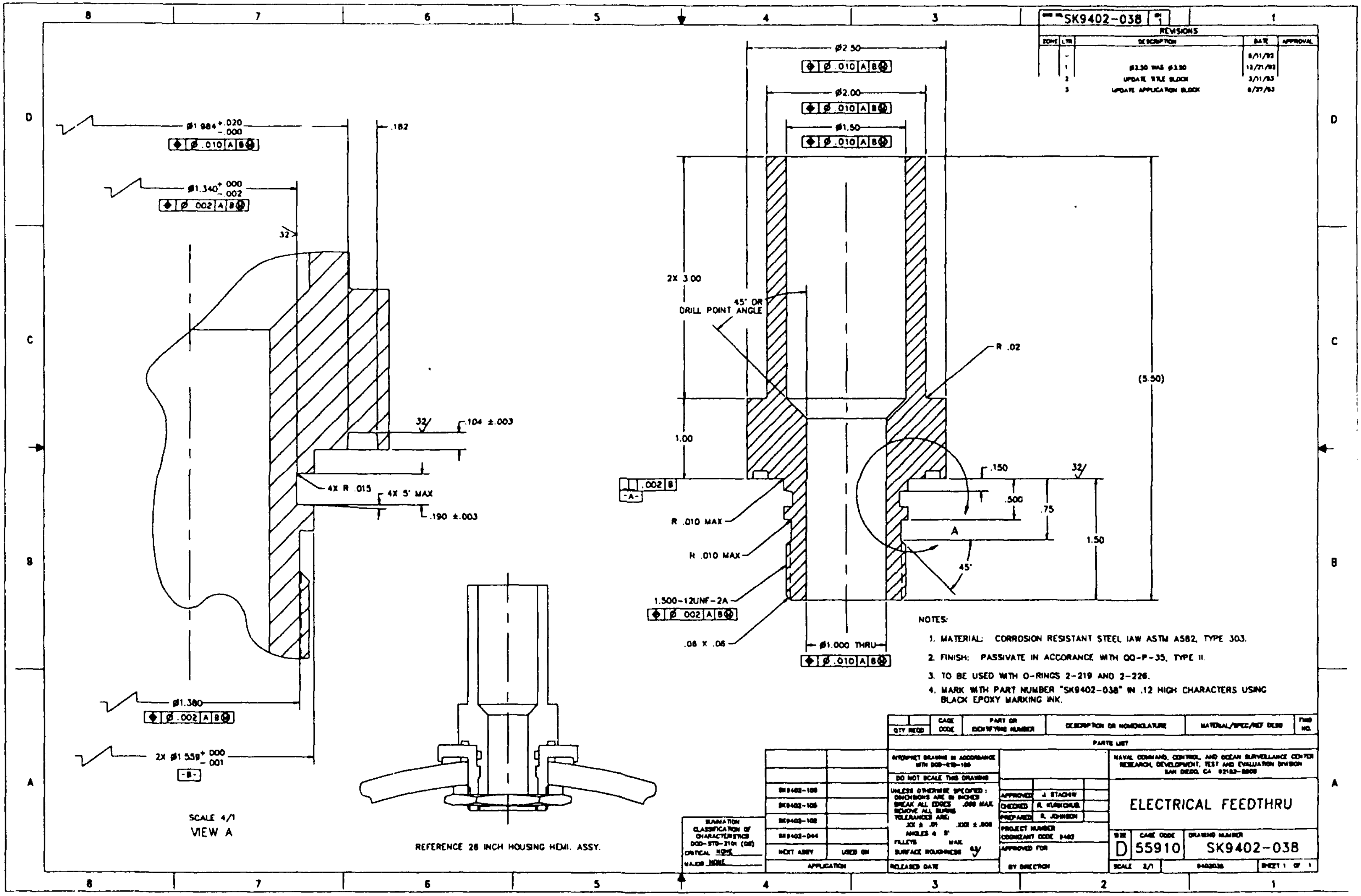


Figure 70. Electrical feed through.

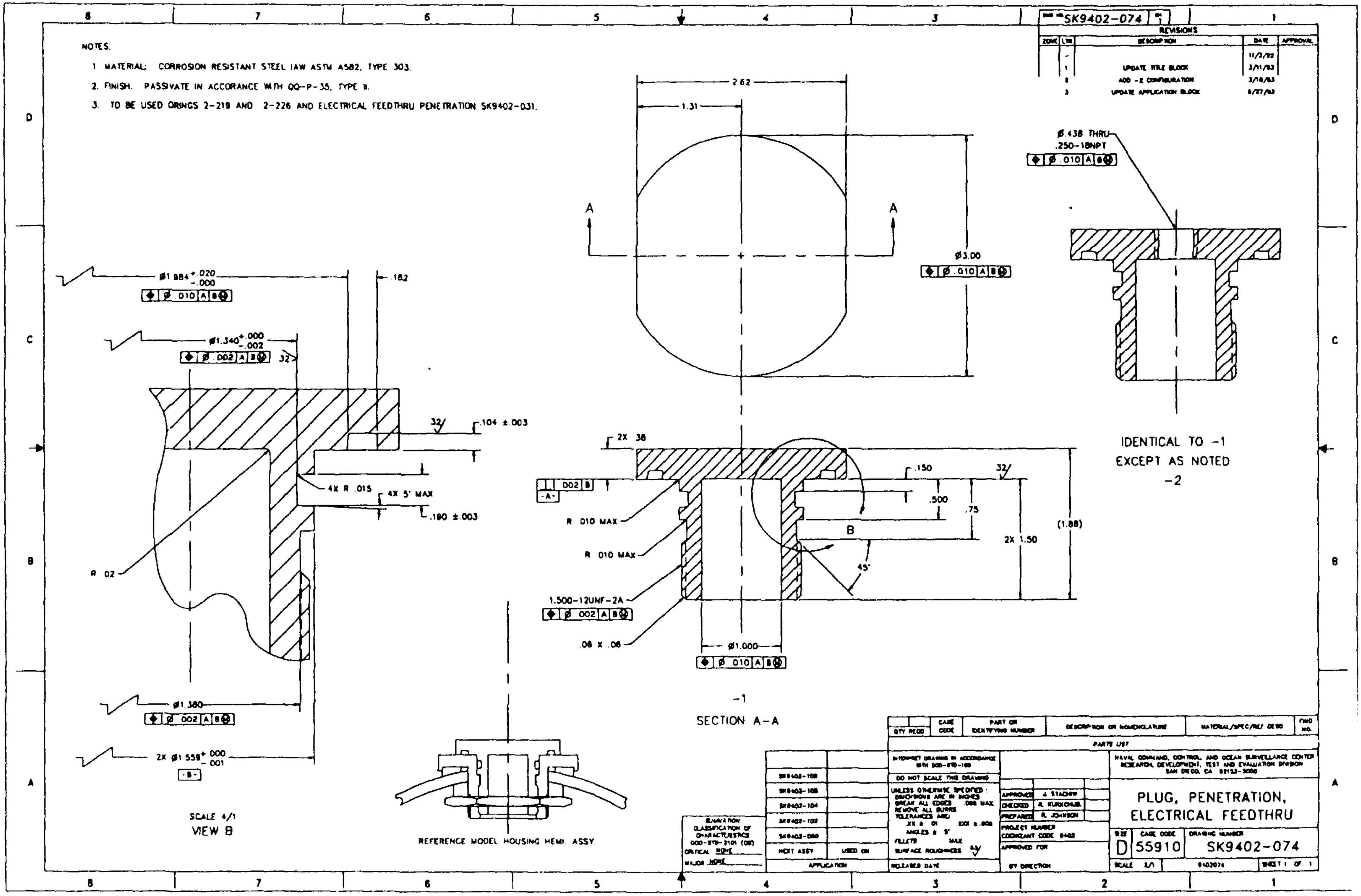


Figure 71. Electrical feed through penetration plug.

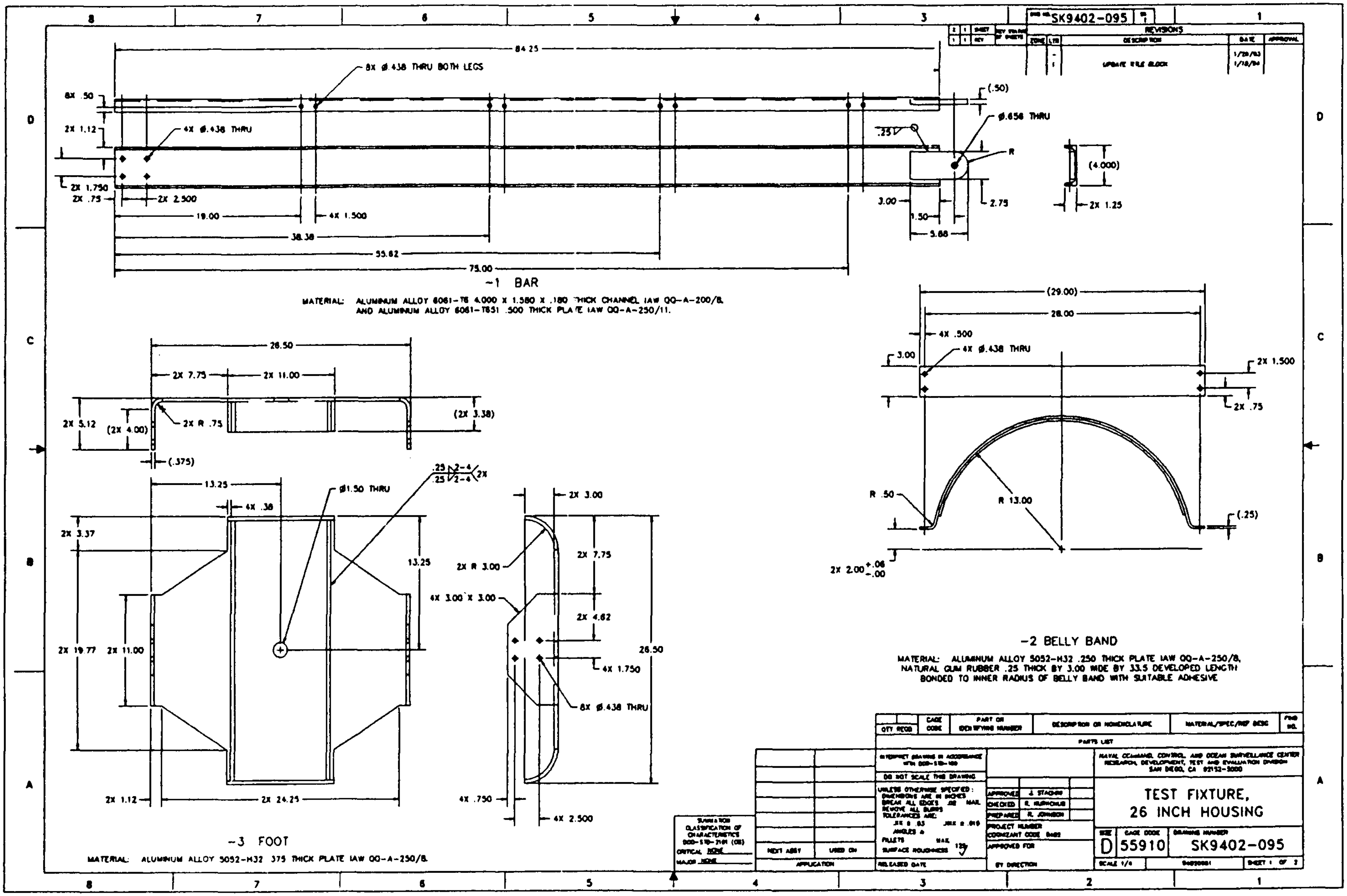


Figure 72. 26-inch-housing pressure-testing fixture, sheet 1.

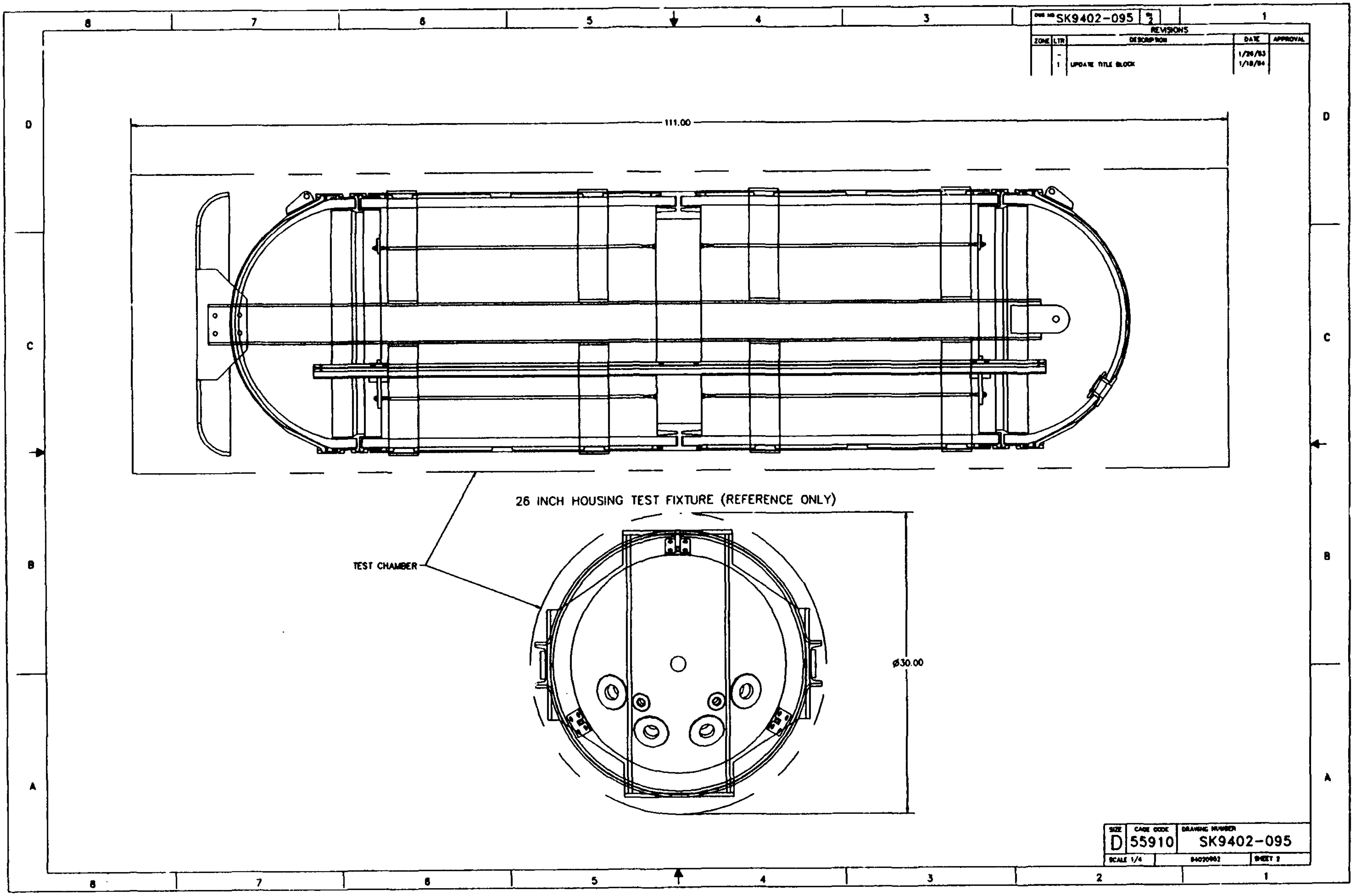


Figure 72. 26-inch-housing pressure-testing fixture, sheet 2.

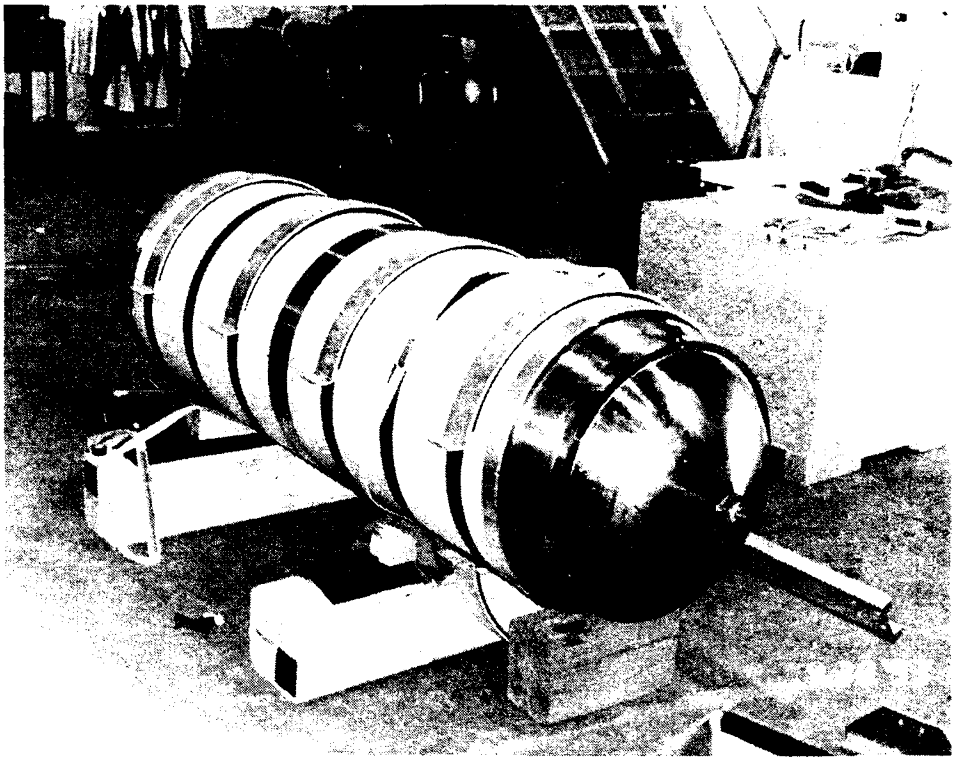


Figure 73. Assembly of test fixture cage before pressure testing of 26-inch-housing cylindrical hull assembly.

Figure 74. 26-inch-housing cylindrical hull mounted inside the pressure-test fixture.

Figure 75. Lowering of 26-inch-housing cylindrical hull into the 30-inch-diameter pressure chamber at SRI. The test fixture centers the ceramic hull inside the chamber.

SK9402-104

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVAL
	-		3/23/93	

NOTES:

1. LUBRICATE O-RINGS (ITEM 2, 11 & 12) WITH SILICONE COMPOUND (ITEM 13) PRIOR TO ASSEMBLY.

2. PROOF TESTING OF THE 26 INCH HOUSING TEST HEMISPHERES (ITEM 1) SHALL BE PERFORMED AS OUTLINED IN NOTE 3 PRIOR TO PRESSURE TESTING ANY OF THE 26 INCH HOUSING SUB ASSEMBLIES SK9402-052, SK9402-053 OR SK9402-054.

3. PRESSURE TESTING SHALL BE PERFORMED IN TAP WATER AT AMBIENT ROOM TEMPERATURE AND SHALL CONSIST OF AT A MINIMUM THE FOLLOWING TEST:

   A. PRESSURIZE TO 10,000 PSI, HOLD FOR 60 MINUTES, DEPRESSURIZE TO 0 PSI.

4. PRESSURE TEST DOCUMENTATION SHALL CONSIST OF THE FOLLOWING:

   A. PHOTOGRAPHS OF THE TEST CONFIGURATION AFTER ASSEMBLY AND AS IT IS LOADED INTO PRESSURE VESSEL.

   B. STRIP CHART WITH PRESSURE HISTORY FOR PROOF TEST.

	QTY REQD -1	CAGE CODE	PART OR IDENTIFYING NUMBER	DESCRIPTION OR NOMENCLATURE	MATERIAL/SPEC/REF DESIG	FIND NO.
	AR			SILICONE COMPOUND	MIL-S-8660	13
	2		2-228	O-RING		12
	2		2-219	O-RING		11
	4		MS16998-18	SCREW, CAP, SOCKET HD, HEX, CRES, .190-32UNF-3A X 1.5L		10
						9
						8
	2	55910	SK9402-098	CLAMP BAND, HEMI TEST, 26 INCH HOUSING		7
	1	55910	SK9402-096	SPACER, 26 INCH HOUSING		6
						5
	1	55910	SK9402-075	PLUG, TEST HEMISPHERE		4
	1	55910	SK9402-074-2	PLUG, PENETRATION, ELECTRICAL FEEDTHRU		3
	2	55910	SK9402-033	O-RING, 26 INCH HOUSING		2
	2	55910	0126898	TEST HEMISPHERE, 26 INCH HOUSING		1

PARTS LIST

SUMMATION CLASSIFICATION OF CHARACTERISTICS DOD-STD-2101 (OS)
CRITICAL NONE
MAJOR NONE

NEXT ASSY	USED ON

APPLICATION

INTERPRET DRAWING IN ACCORDANCE WITH DOD-STD-100

DO NOT SCALE THIS DRAWING

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES
BREAK ALL EDGES MAX.
REMOVE ALL BURRS
TOLERANCES ARE:
.XX ± .XXX ±
ANGLES ±
FILLETS MAX.
SURFACE ROUGHNESS ✓

RELEASED DATE

APPROVED	J. STACHIW
CHECKED	R. KURKCHUB
PREPARED	R. JOHNSON

PROJECT NUMBER
COGNIZANT CODE 9402
APPROVED FOR
BY DIRECTION

NAVAL COMMAND, CONTROL, AND OCEAN SURVEILLANCE CENTER
RESEARCH, DEVELOPMENT, TEST AND EVALUATION DIVISION
SAN DIEGO, CA 92152-5000

TEST CONFIGURATION,
TEST HEMISPHERE,
26 INCH HOUSING

SIZE D | CAGE CODE 55910 | DRAWING NUMBER SK9402-104

SCALE NONE | 94021041 | SHEET 1 OF 3

Figure 76. Proof configuration for 26-inch-housing test hemispheres, sheet 1.

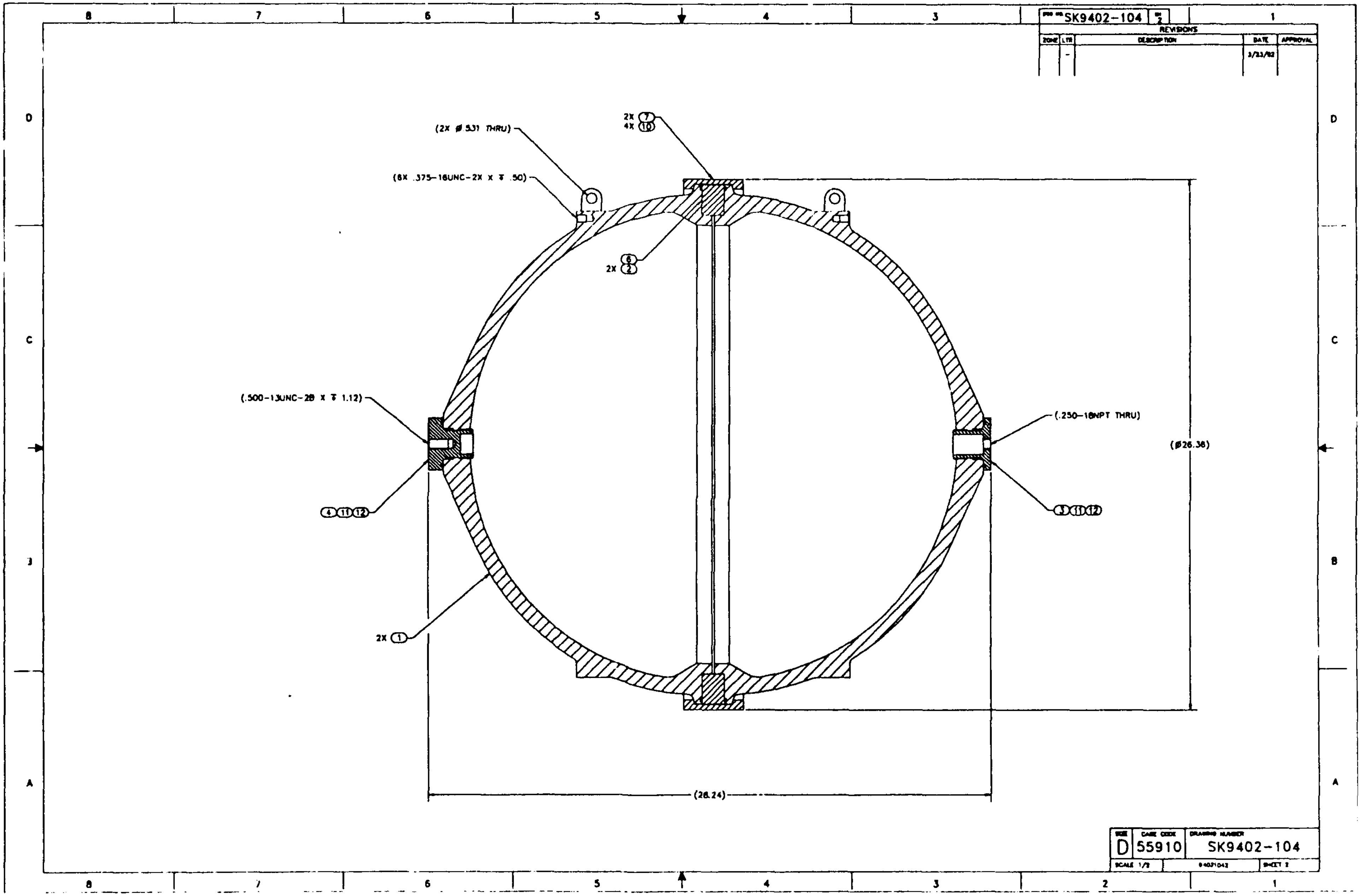


Figure 76. Proof configuration for 26-inch-housing test hemispheres, sheet 2.

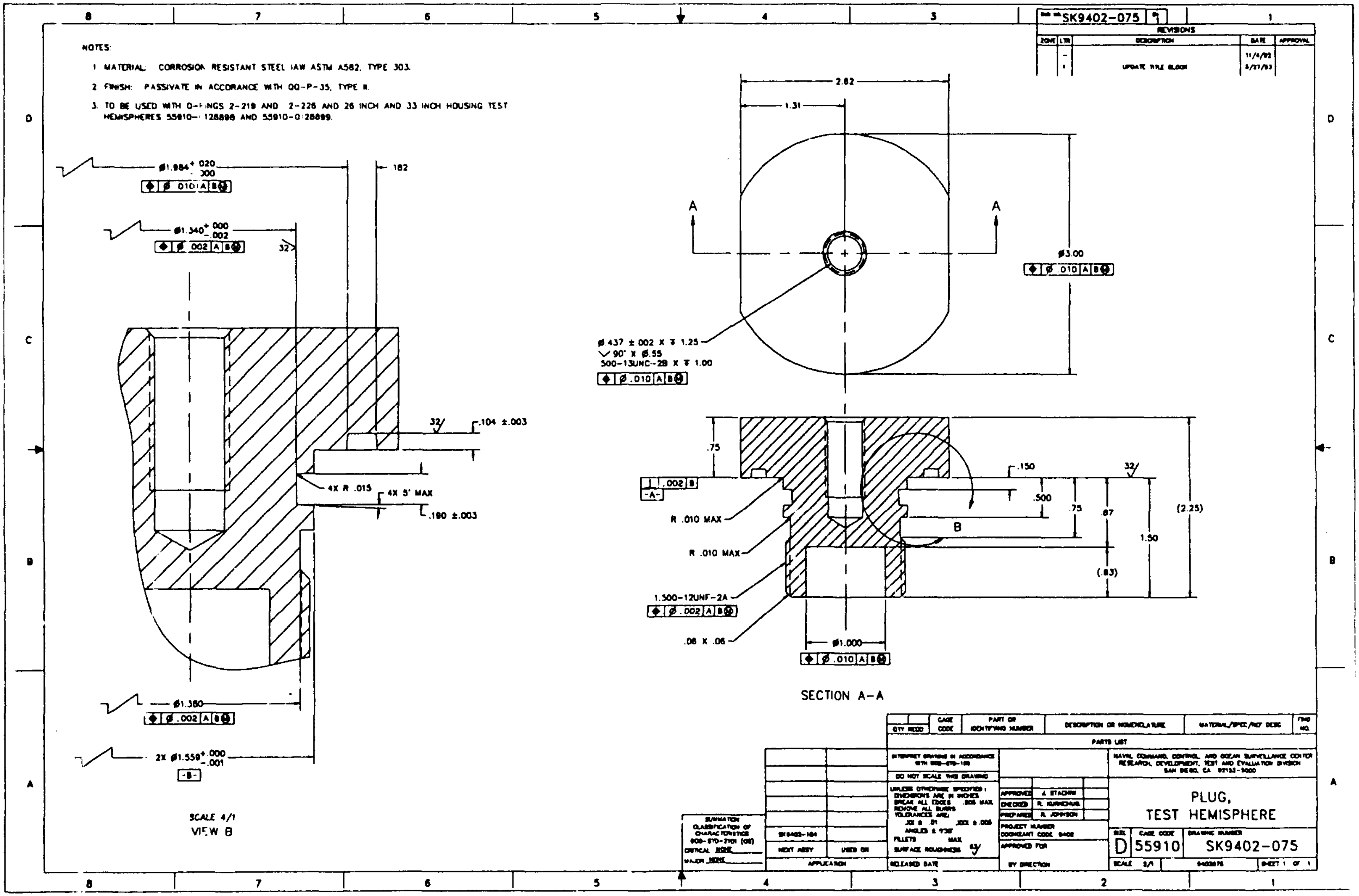


Figure 77. Test hemisphere plug.

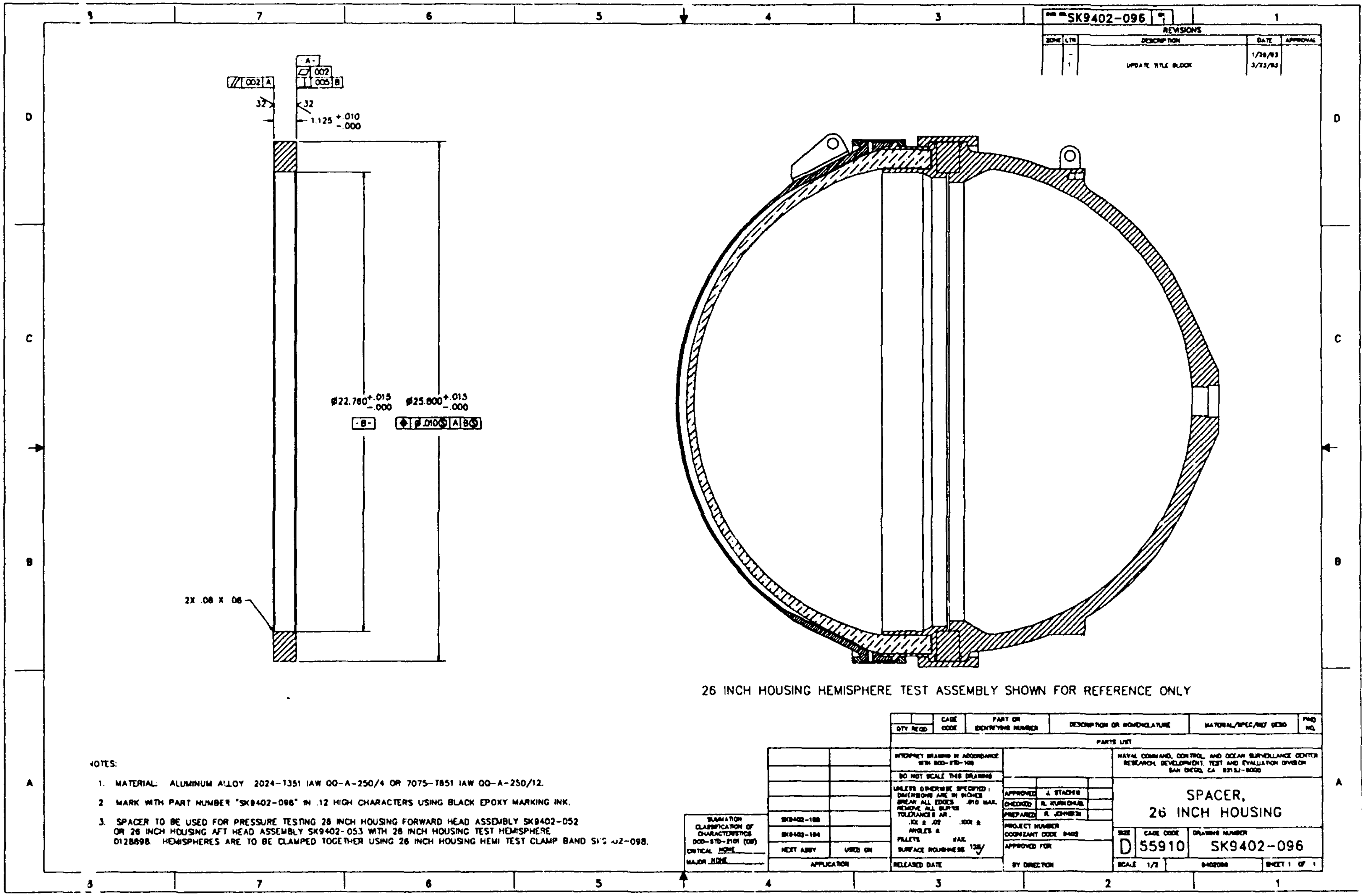


Figure 78. 26-inch-housing spacer.

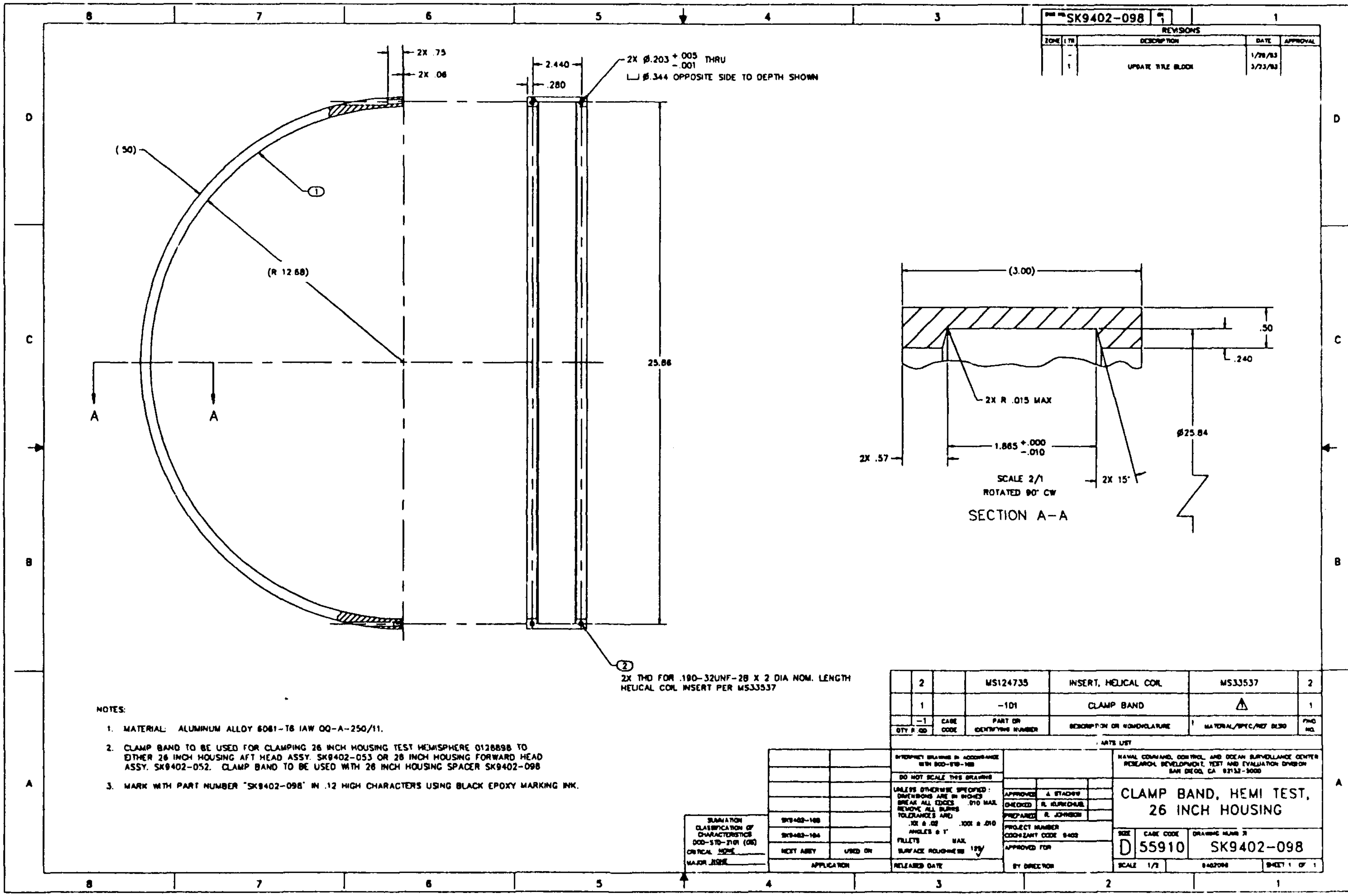


Figure 79. 26-inch-housing test hemisphere clamp band.

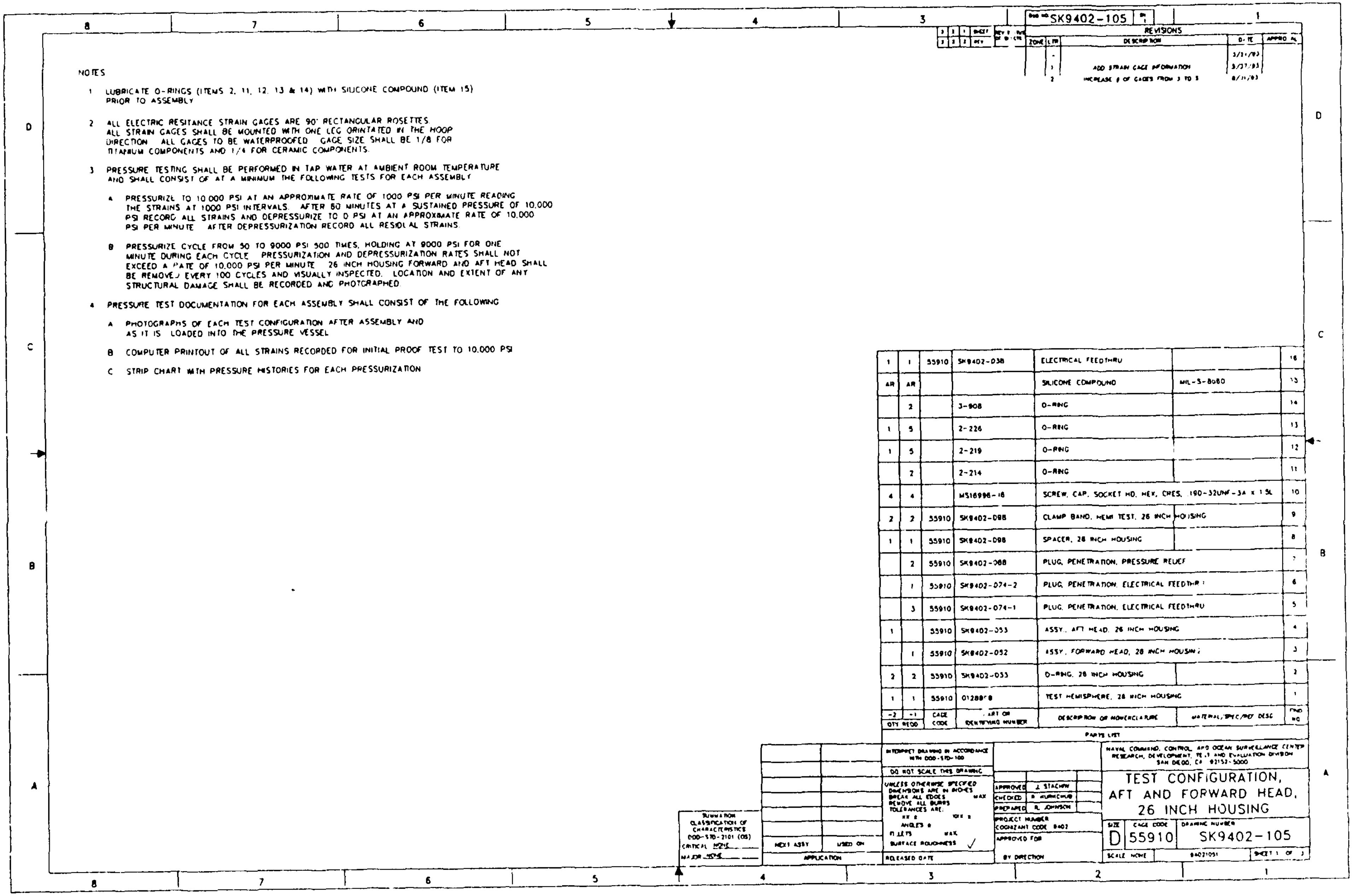


Figure 80. Test configurations for 26-inch-housing aft and forward head, sheet 1.

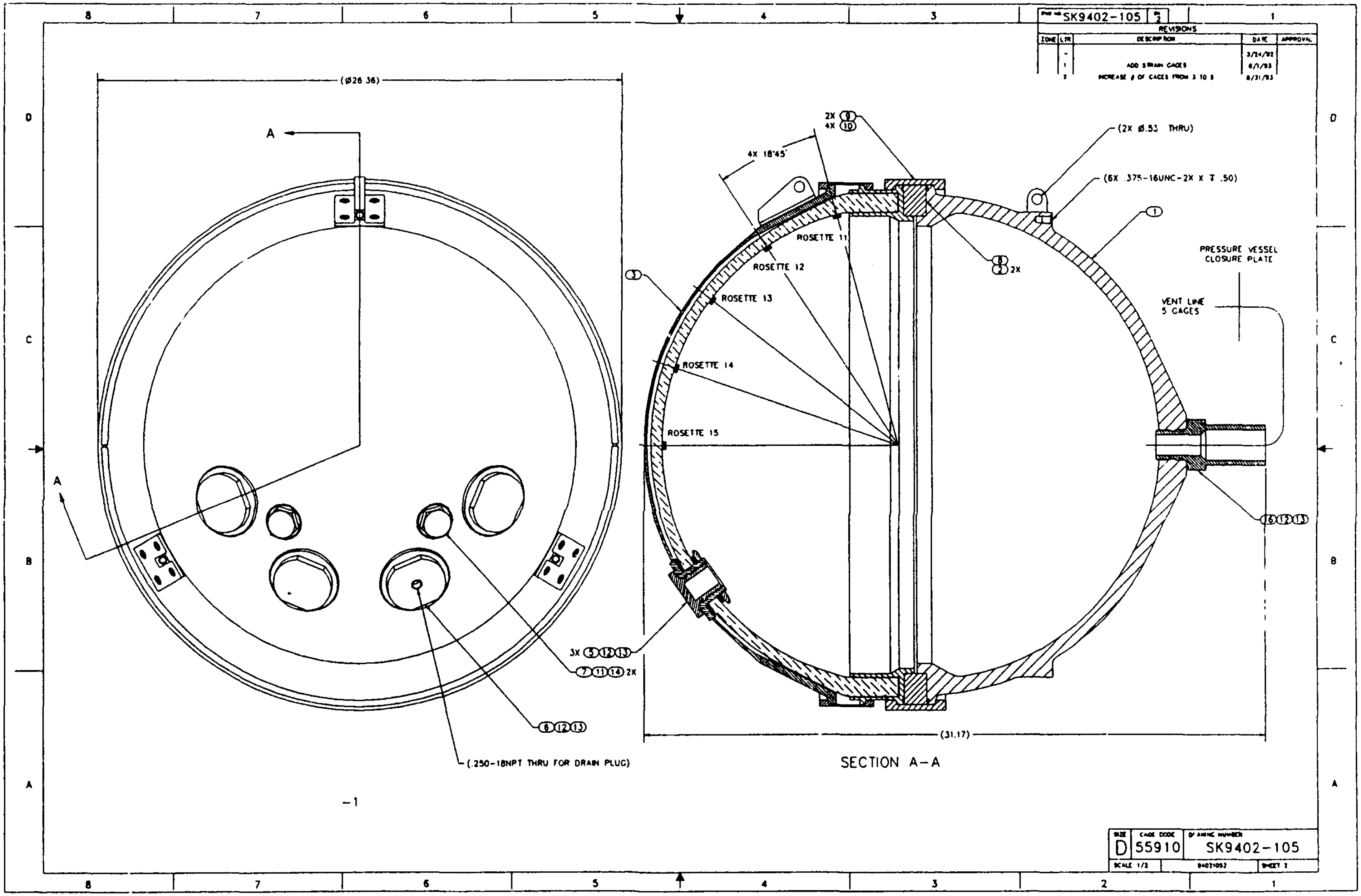


Figure 80. Test configurations for 26-inch-housing aft and forward head, sheet 2.

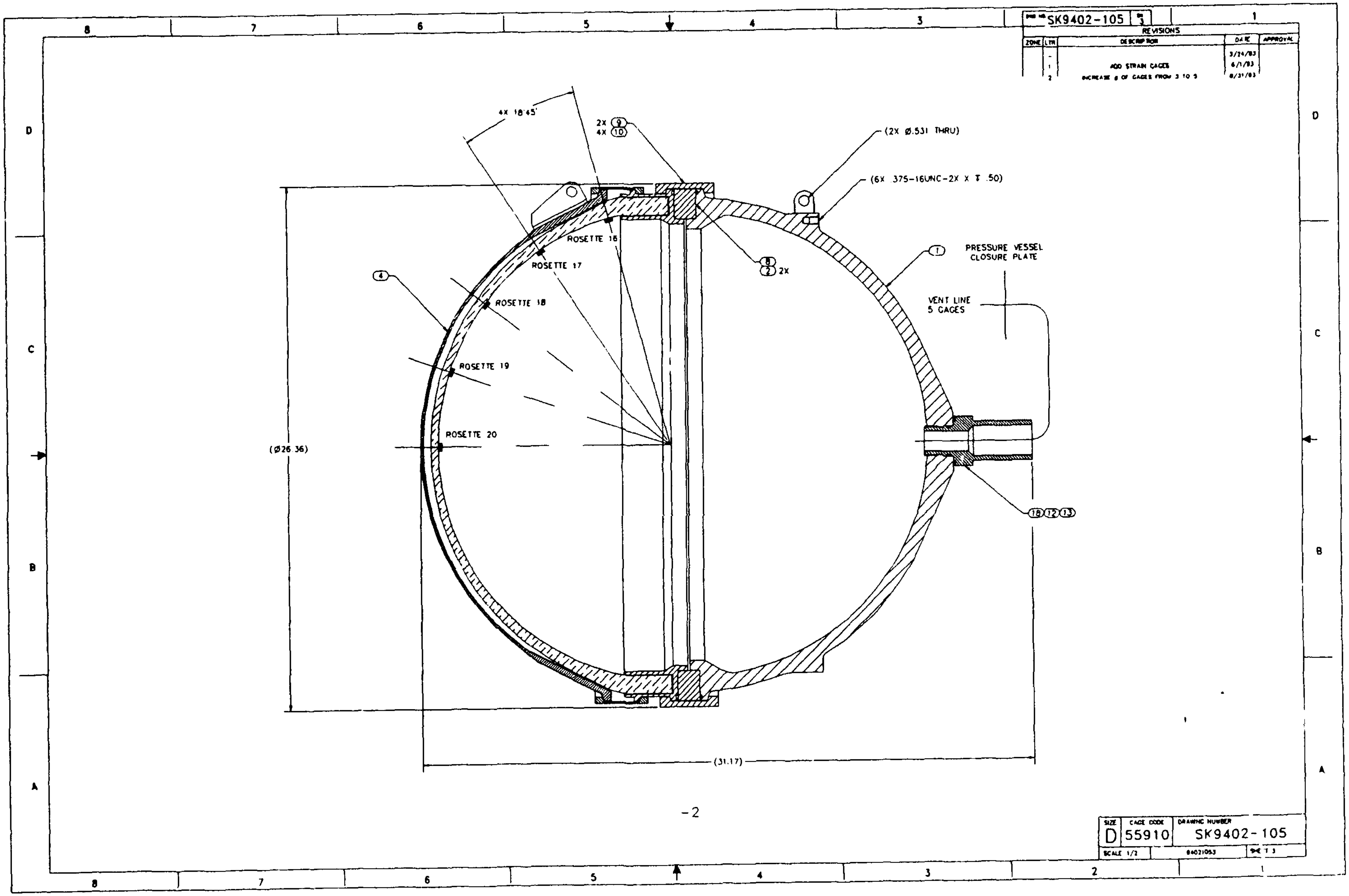


Figure 80. Test configurations for 26-inch-housing aft and forward head, sheet 3.

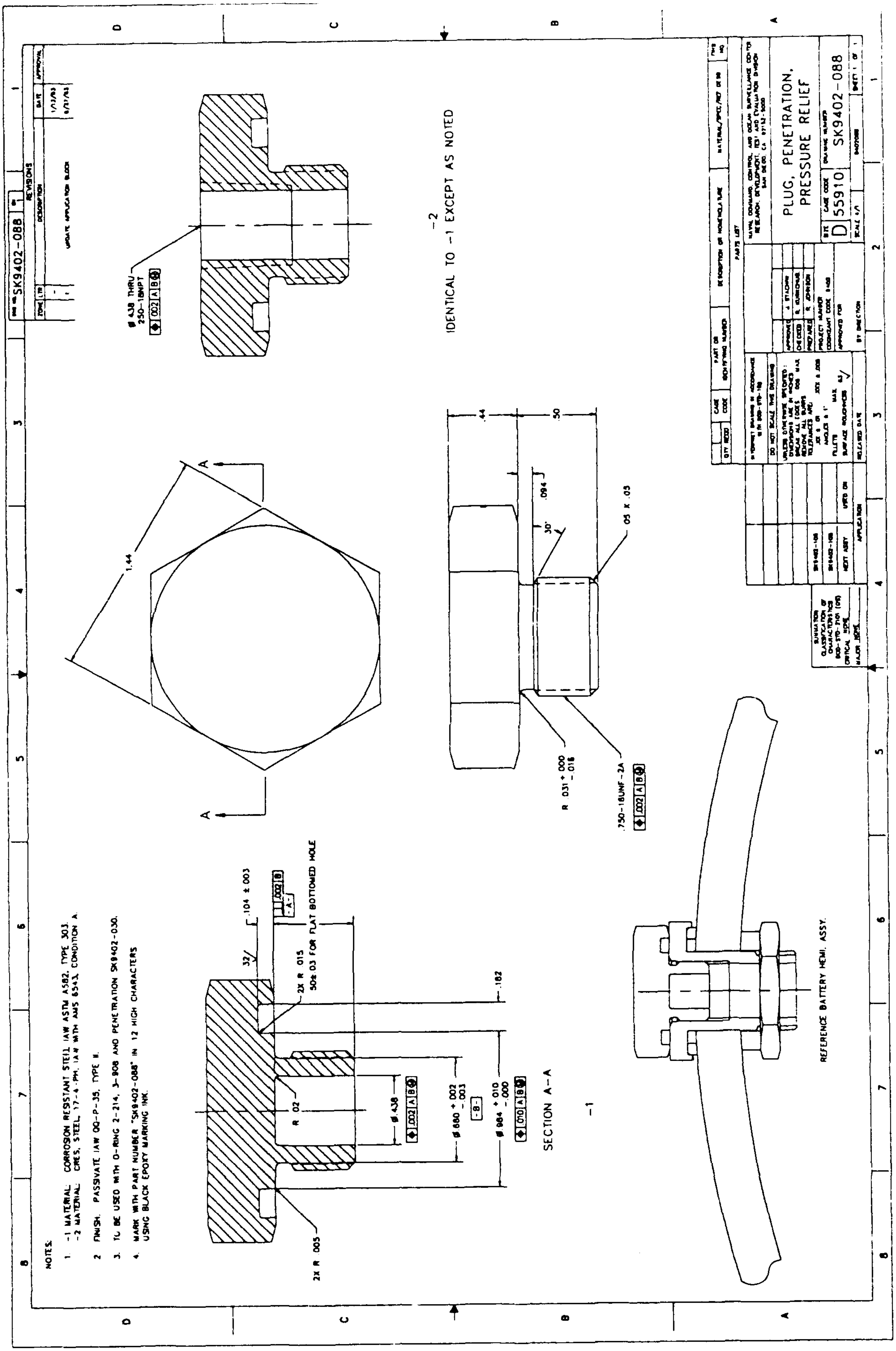


Figure 81. Pressure-relief penetration plug.

Figure 82. Lowering of the 26-inch-housing aft head assembly with test fixtures into the pressure chamber. The test fixture keeps the housing from floating up in the chamber.

Figure 83. 26-inch-housing forward head assembly prior to placement into the test fixture.

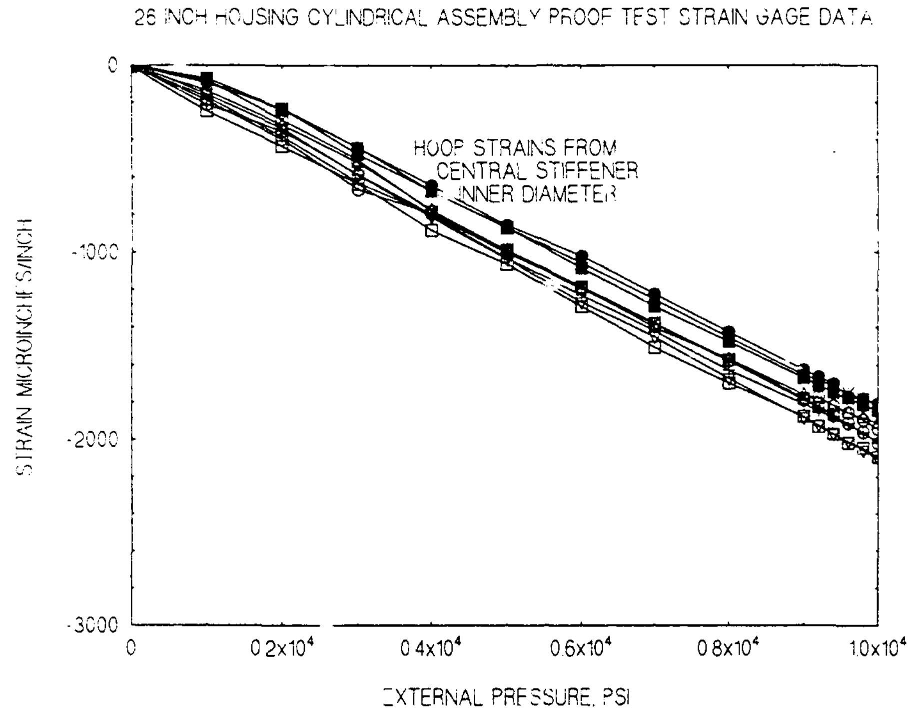


Figure 84. Hoop strains on the interior surface of the central stiffener used in the cylindrical hull assembly.

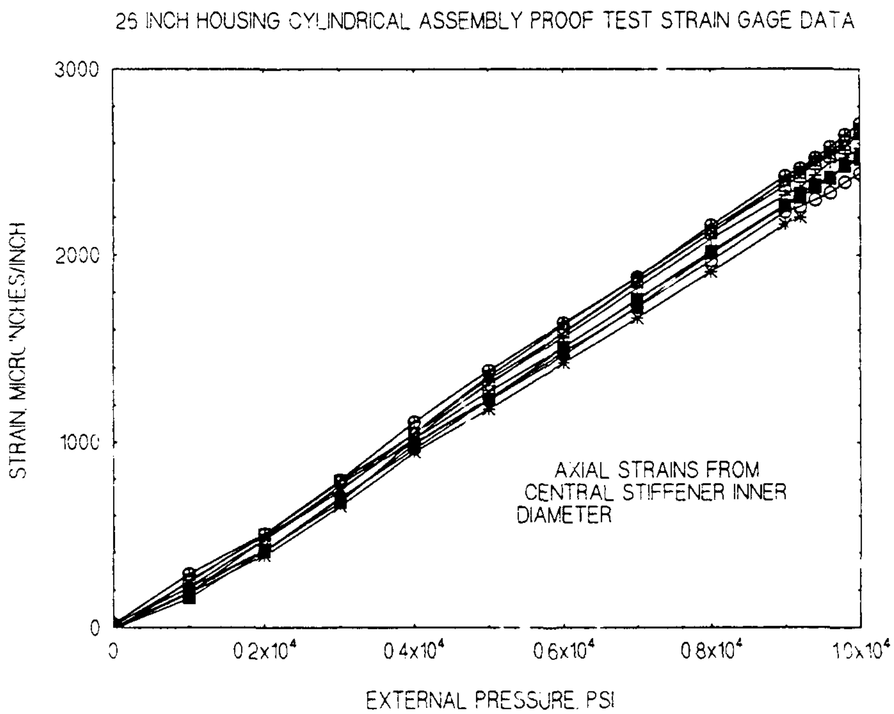


Figure 85. Axial strains on the interior surface of the central stiffener used in the cylindrical hull assembly.

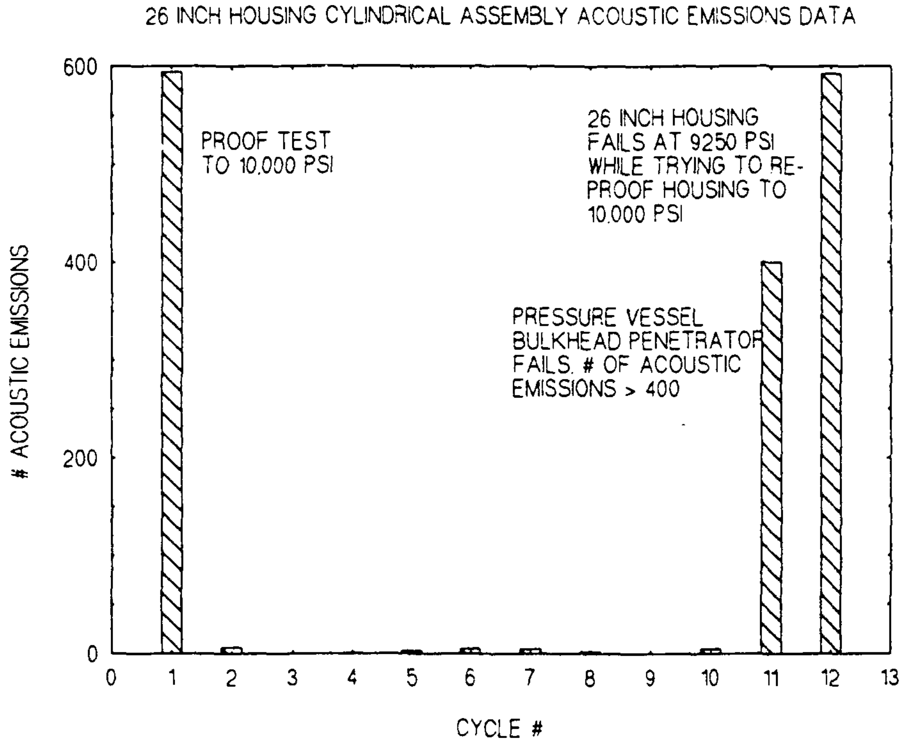


Figure 86. Acoustic emissions data for each pressure test performed on the cylindrical hull assembly.

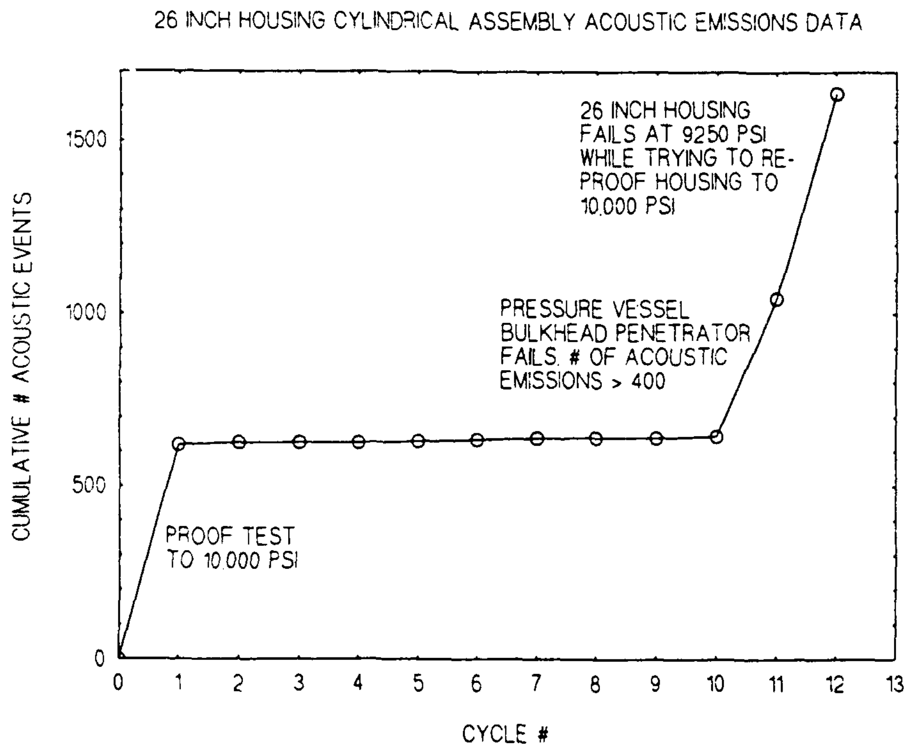


Figure 87. Cumulative acoustic emissions data for all pressure testing performed on the cylindrical hull assembly.

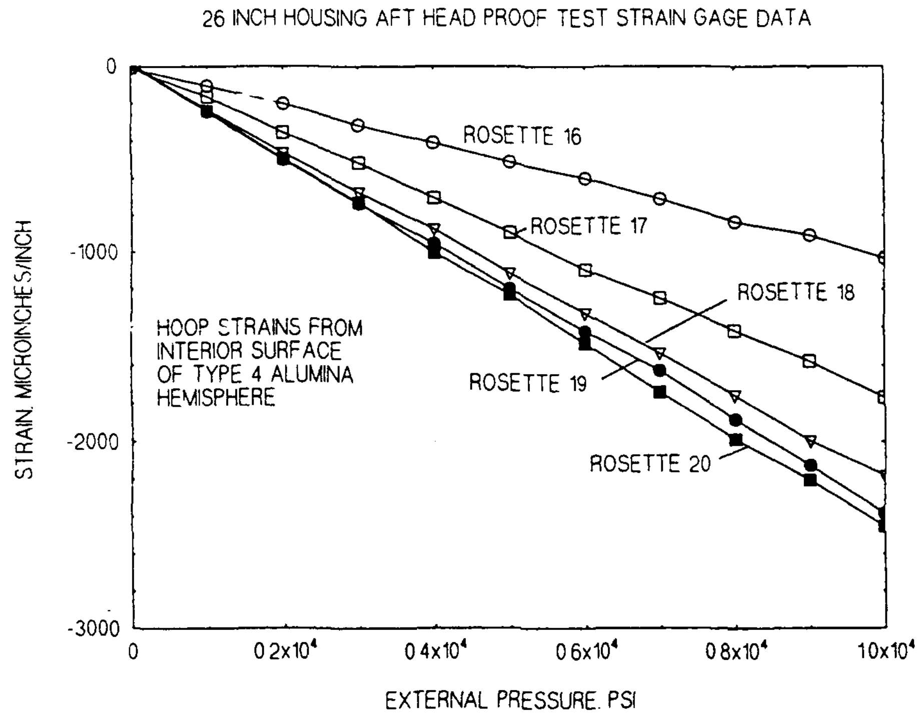


Figure 88. Hoop strains on the interior surface of the dimensionally qualified Type 4 alumina hemisphere used in the aft head assembly.

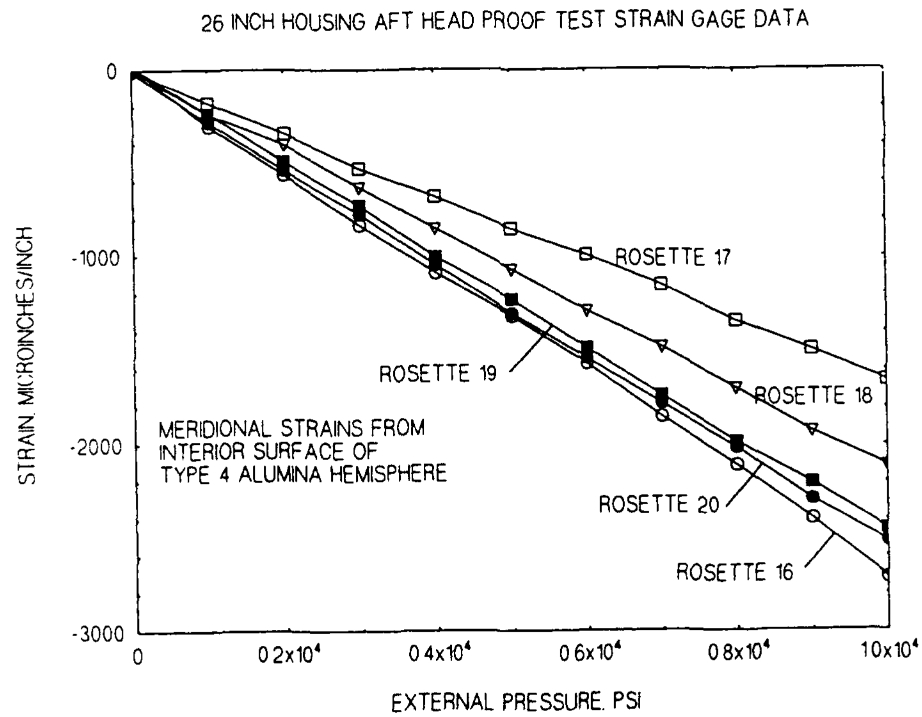


Figure 89. Meridional strains on the interior surface of the dimensionally qualified Type 4 alumina hemisphere used in the aft head assembly.

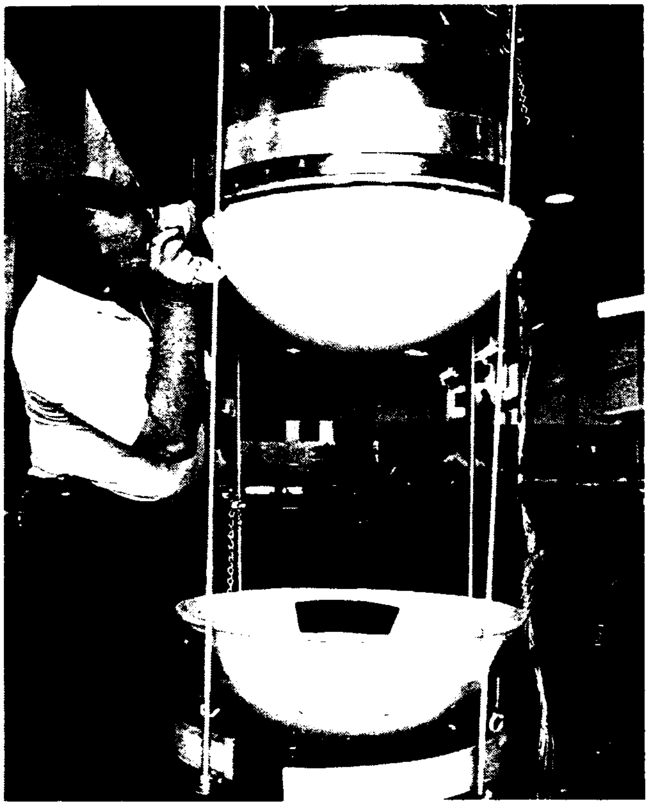


Figure 90. Periodic inspection of the aft head assembly during pressure cycling to 9,000-psi external pressure.

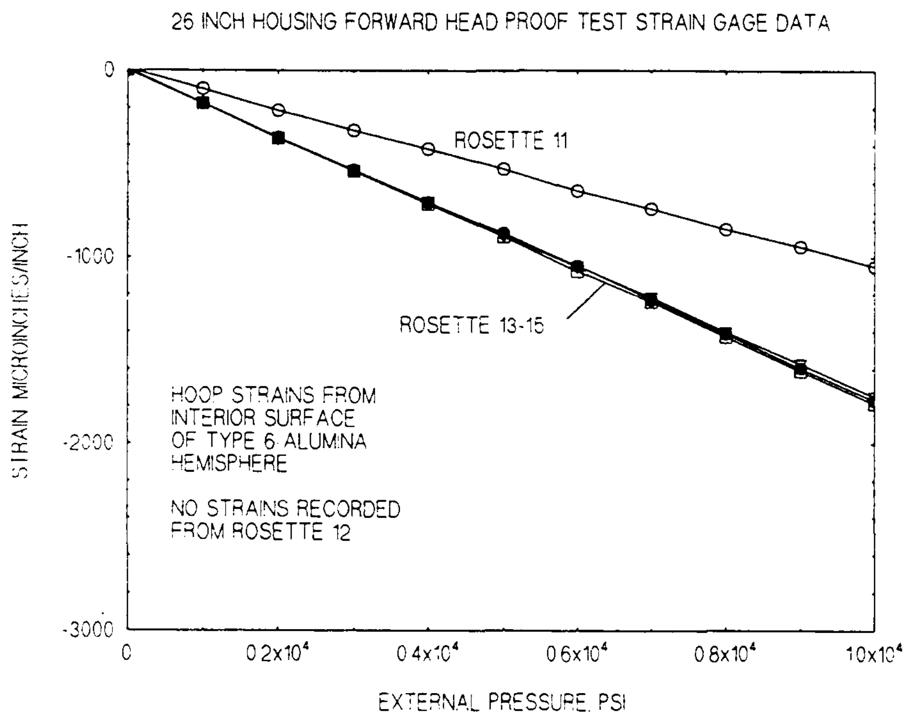


Figure 91. Hoop strains on the interior surface of the Type 6 alumina hemisphere used in the forward head assembly.

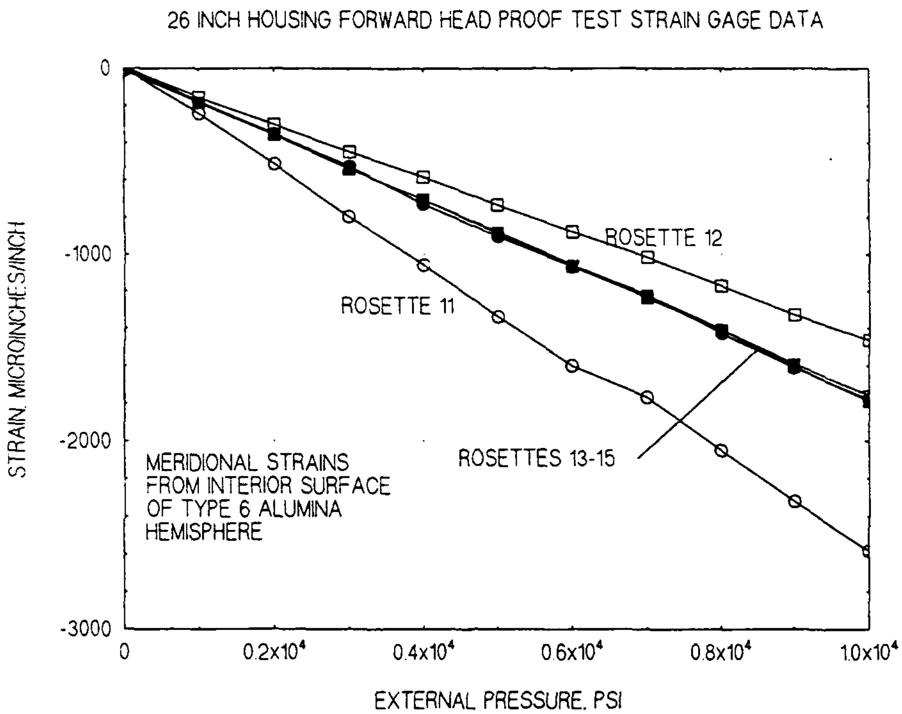


Figure 92. Meridional strains on the interior surface of the Type 6 alumina hemisphere used in the forward head assembly.

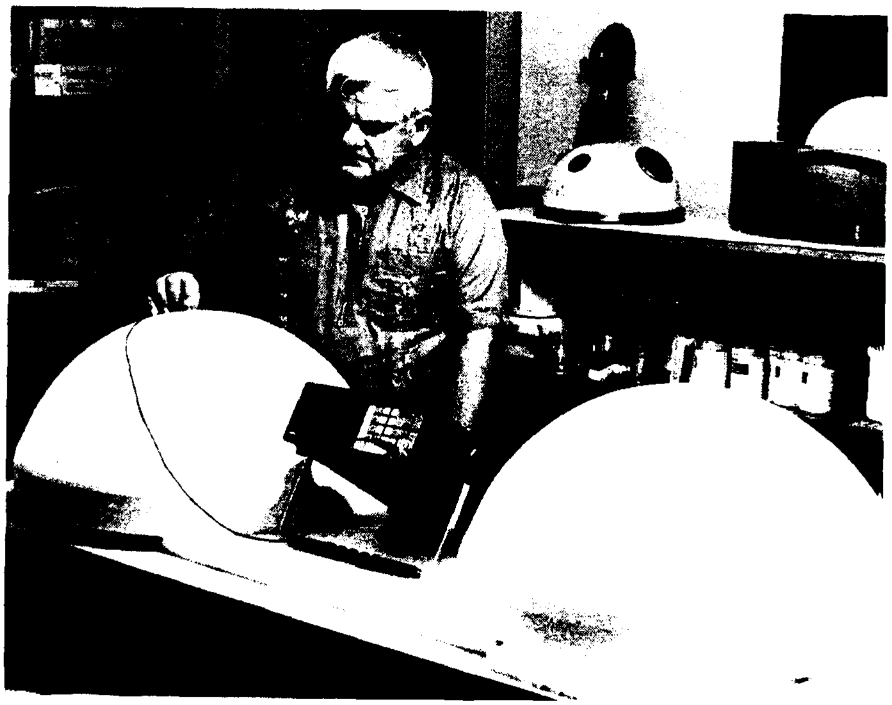


Figure 93. The wall thickness of the Type 4 ceramic hemispheres was measured with a hand-held pulse-echo ultrasonic transducer.

Figure 94. External pressure housing consisting of two Type 4 alumina hemispheres.

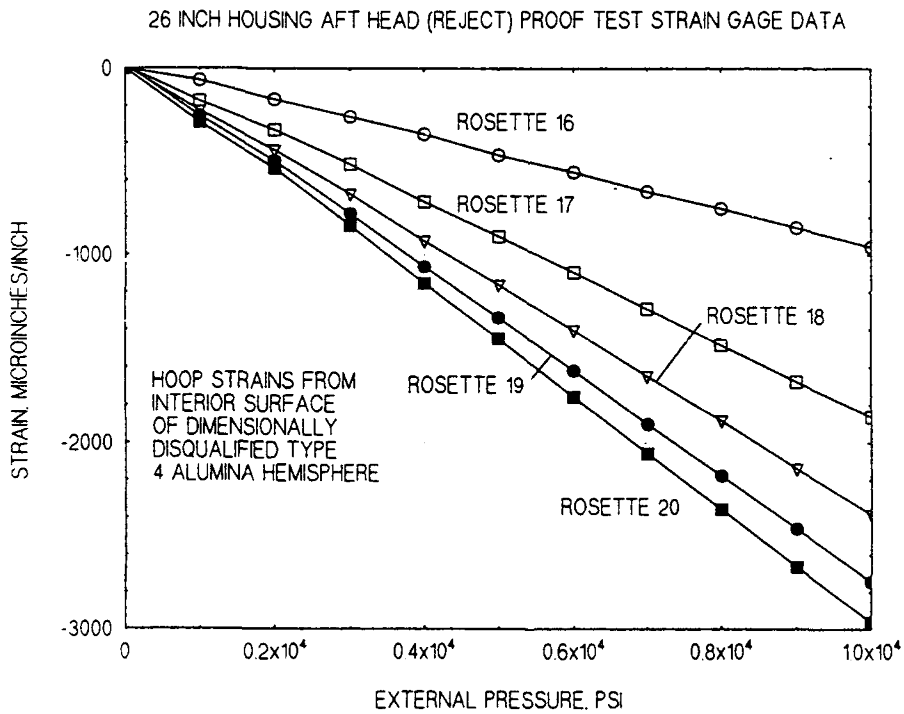


Figure 95. Hoop strains on the interior surface of the dimensionally disqualified Type 4 alumina hemisphere intended for use in the aft head assembly.

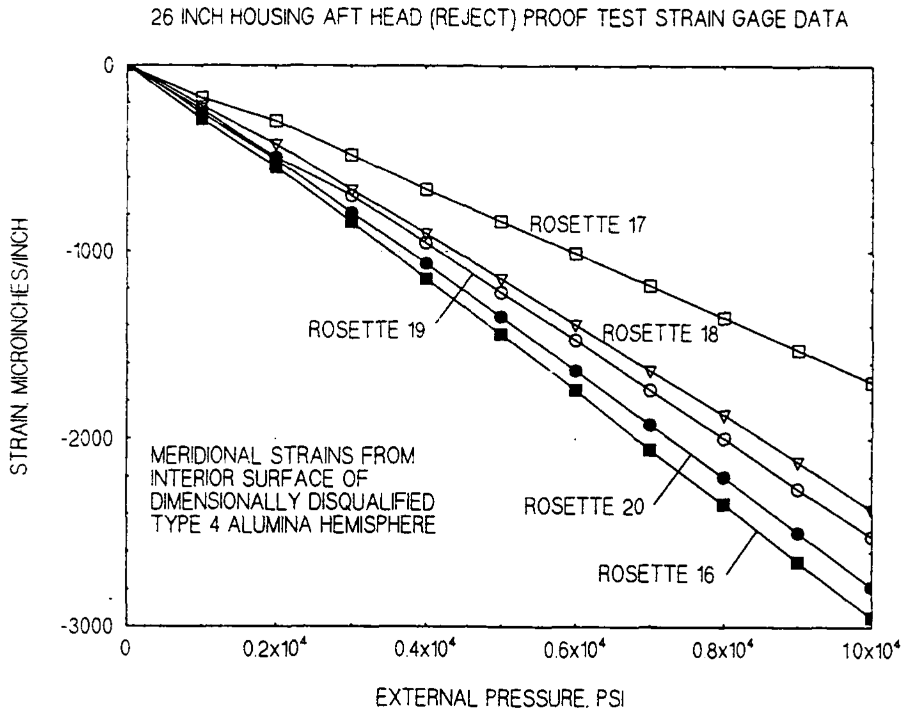


Figure 96. Meridional strains on the interior surface of the dimensionally disqualified Type 4 alumina hemisphere intended for use in the aft head assembly.

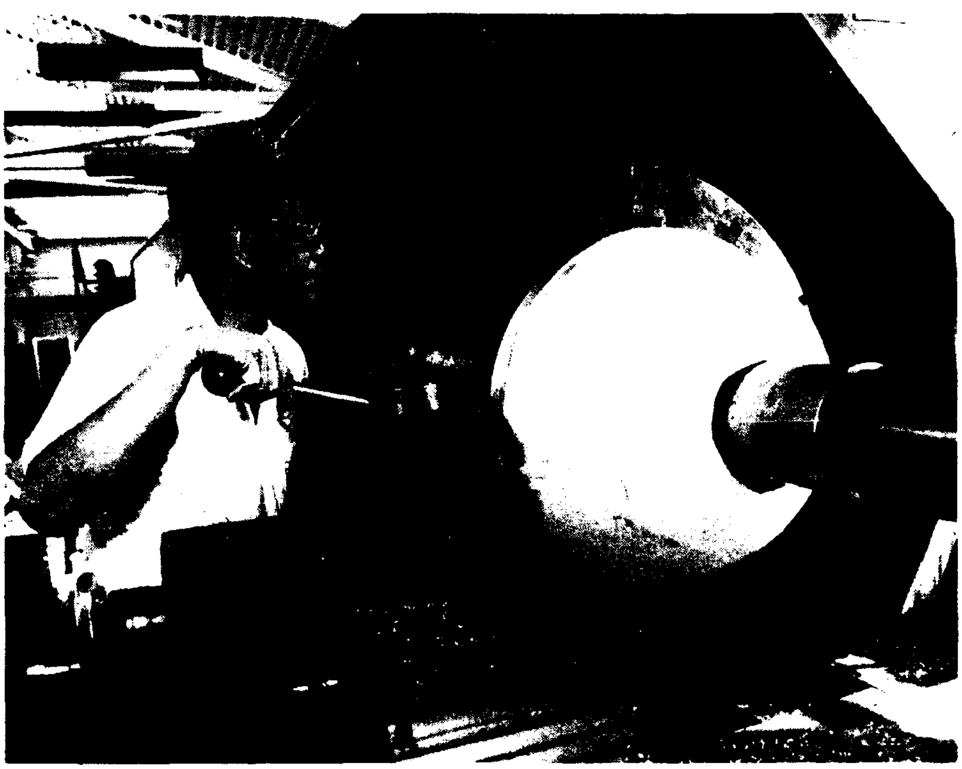


Figure 97. Removal of the exterior flange of the end-cap joint ring used on the dimensionally qualified Type 4 alumina hemisphere for post-service ultrasonic inspection of the bearing-surface region.

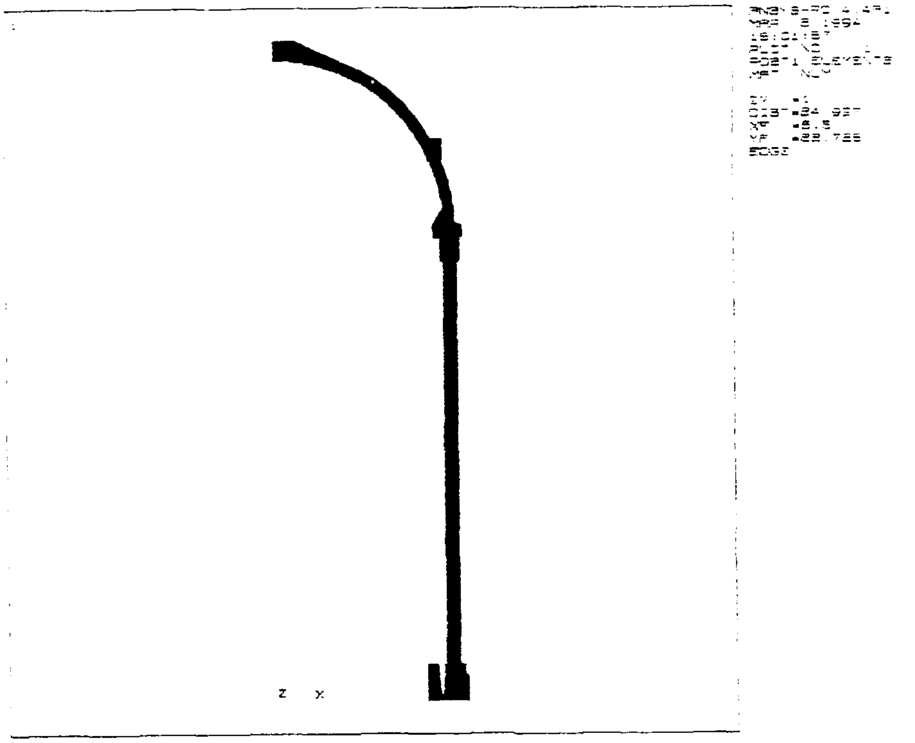


Figure 98. FEA solid model of pressure-test configuration for the cylindrical hull assembly.

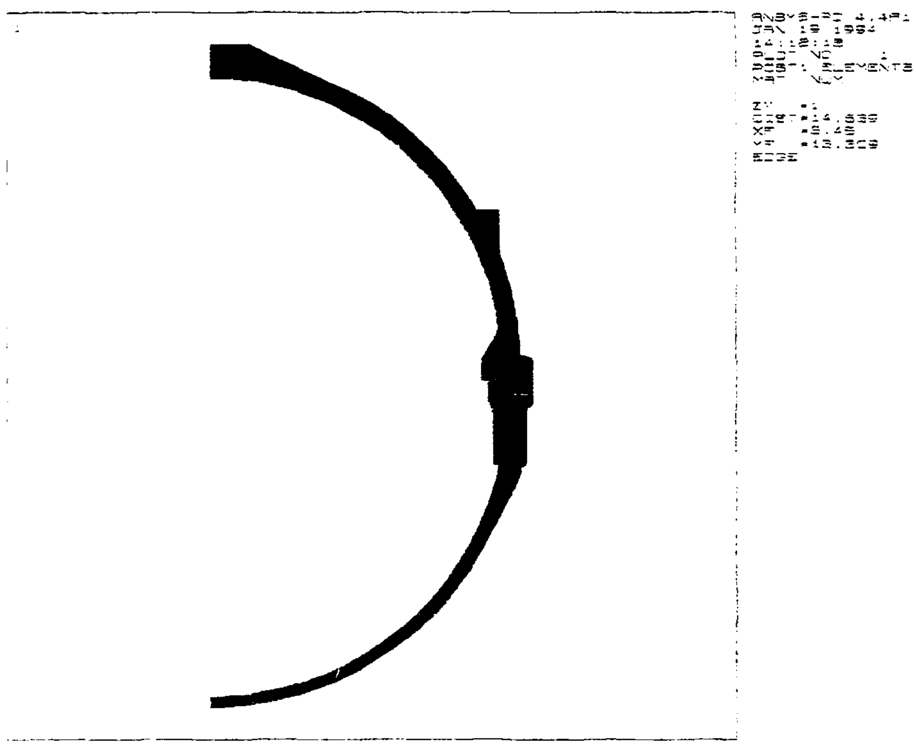


Figure 99. FEA solid model of pressure-test configuration for aft head assembly using a Type 4 alumina hemisphere.

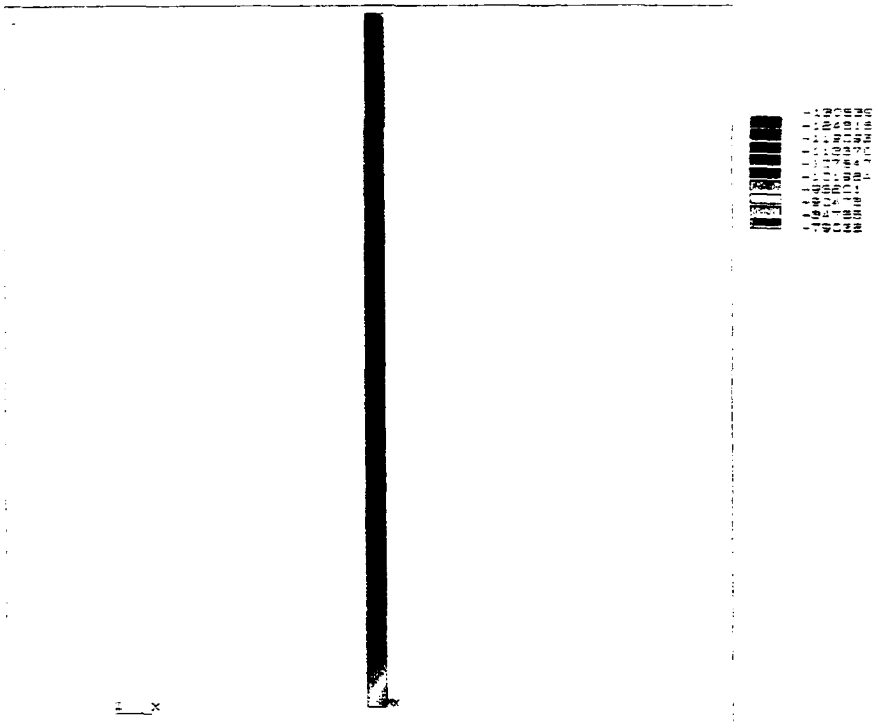


Figure 100. Minimum principal stresses at 9,000-psi external pressure in the alumina cylinder used for the cylindrical hull assembly.

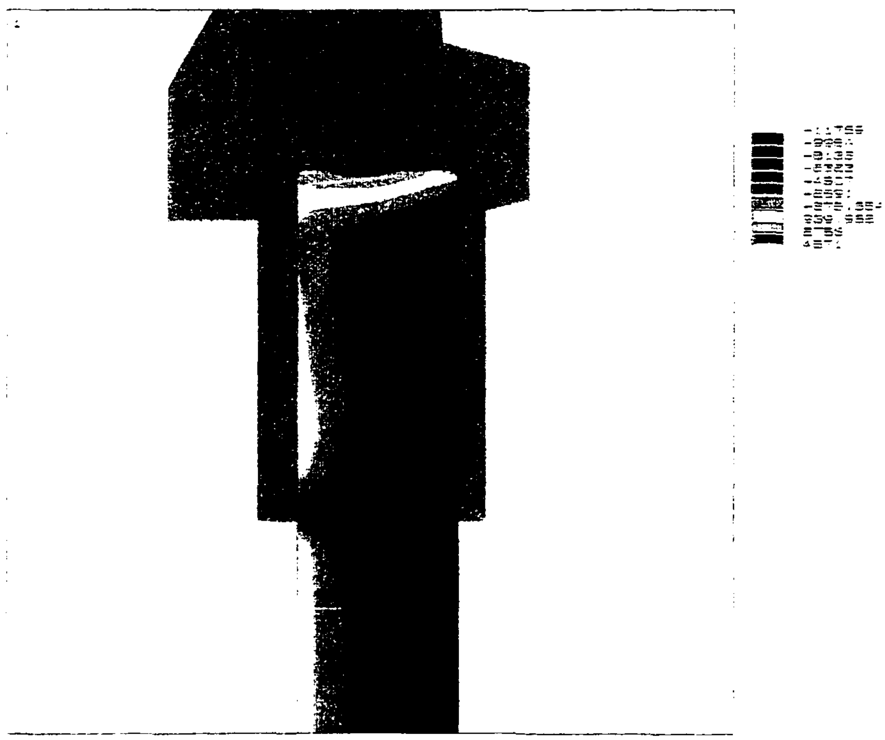


Figure 101. Maximum principal stresses at 9.000-psi external pressure in the alumina cylinder used for cylindrical hull assembly.

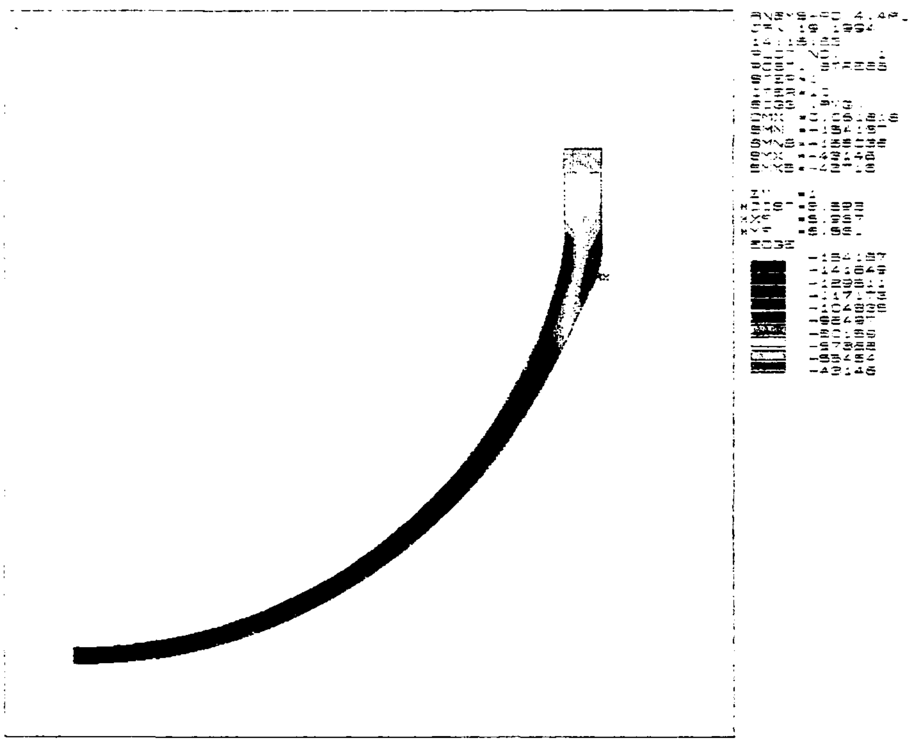


Figure 102. Minimum principal stresses at 9,000-psi external pressure in the Type 4 alumina hemisphere used for the aft head assembly.

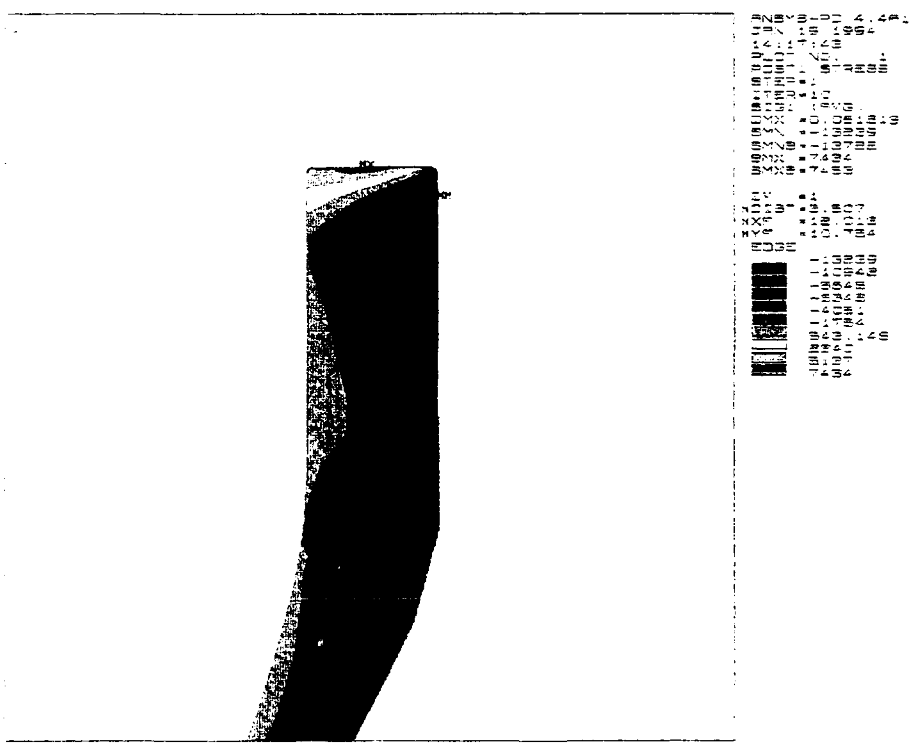


Figure 103. Maximum principal stresses at 9,000-psi external pressure in the bearing surface region of the Type 4 alumina hemisphere used for the aft head assembly.

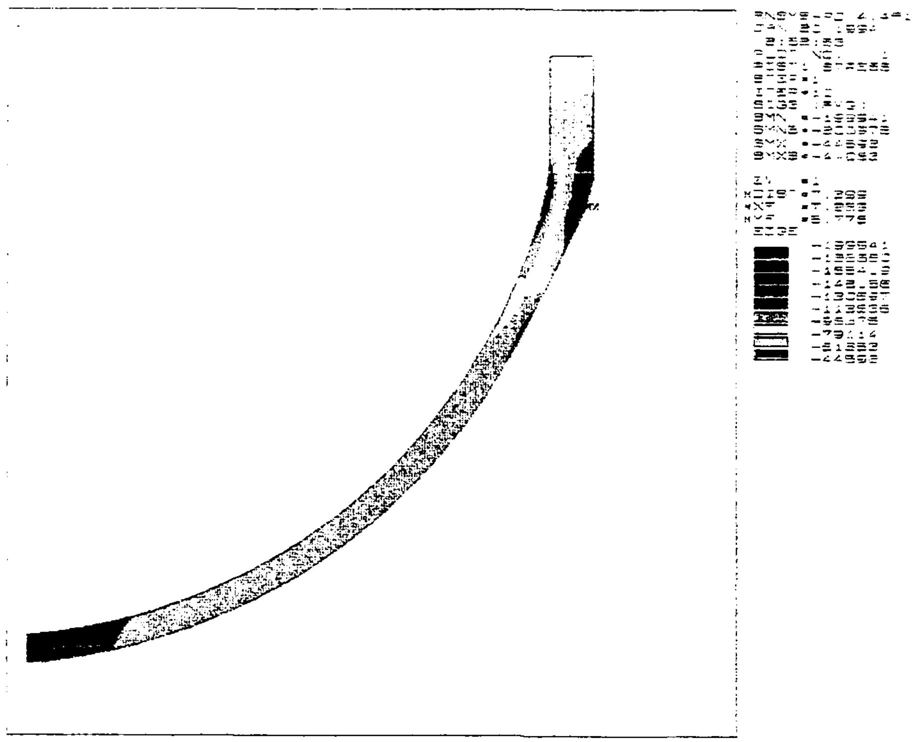


Figure 104. Minimum principal stresses at 9,000-psi external pressure in the Type 6 alumina hemisphere used for the forward head assembly.

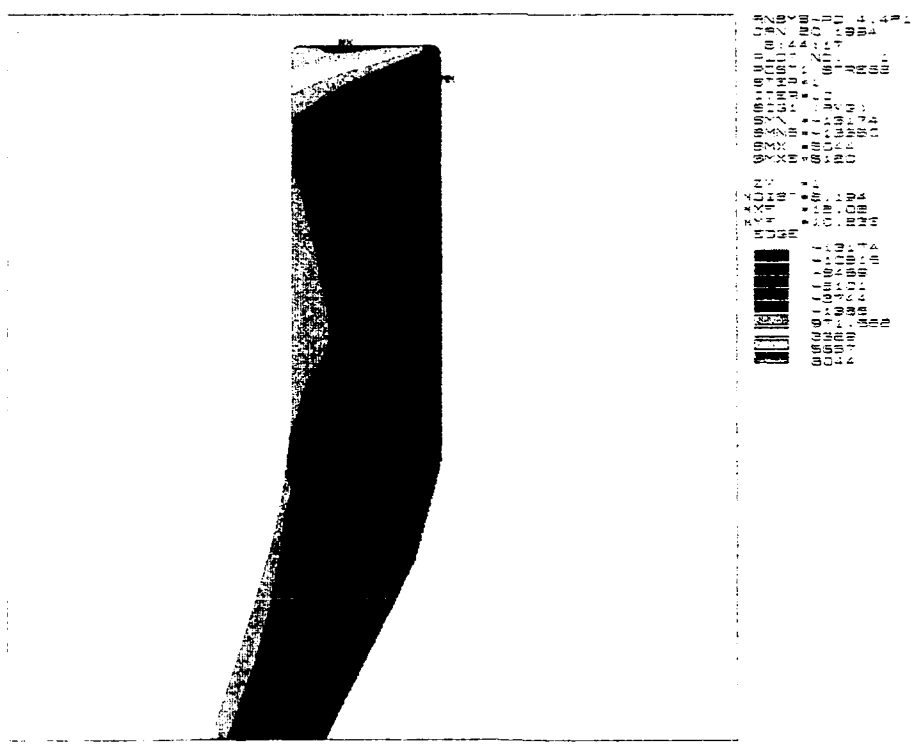


Figure 105. Maximum principal stresses at 9,000-psi external pressure in the Type 6 alumina hemisphere used for the forward assembly.

Table 1. Material property data for WESGO alumina-ceramic compositions.

WESGO GTE

Technical Ceramics
and Metals

Wesgo® Dense Alumina & Properties

Property	Unit	Temp.	AL-500	AL-600	AL-300	AL-995
Al_2O_3 Content	%		94.0	96.0	97.6	99.5
Flexural Strength	psi	Room	50,000	53,000	43,000	45,000
	MPa	Temp. (RT)	345	365	296	310
Compressive Strength	psi		>300,000	>300,000	>250,000	>300,000
	MPa	R.T.	>2070	>2070	>1720	>2070
Density	lbs/in^3		0.132	0.134	0.136	0.139
	g/cc	R.T.	3.67	3.72	3.76	3.86
Porosity	% water absorption		vacuum tight 0.00	vacuum tight 0.00	vacuum tight 0.00	vacuum tight 0.00
Color	—		white	white	white	white
Hardness	Rockwell 45N		78	79	75	81
Thermal Conductivity	BTU/ft hr °F		11.9	14.8	15.5	16.9
	W/m °K	R.T.	20.5	25.6	26.8	29.3
Coefficient of Linear Thermal Expansion	$10^{-6}/°C$	25°— 200°C	6.3	6.4	6.9	6.9
		200°— 400°C	7.5	7.6	7.8	7.8
		400°— 600°C	8.0	8.2	8.5	8.3
		600°— 800°C	8.6	8.7	8.8	9.0
		800°—1000°C	9.1	9.0	9.0	9.4
	$10^{-6}/°F$	77°— 390°F	3.5	3.6	3.8	3.8
		390°— 750°F	4.2	4.2	4.3	4.3
		750°—1110°F	4.4	4.6	4.7	4.6
		1110°—1470°F	4.8	4.8	4.9	5.0
		1470°—1830°F	5.1	5.0	5.0	5.2
Maximum Working Temperature	°C		1600	1620	1650	1725
	°F		2910	2950	3000	3150
Dielectric Strength (.100" thick under oil)	D.C. volts/mil	R.T.	650	675	1100	800
	D.C. kilovolts/mm		25.6	26.6	43.3	31.5
Te Value	°C		>950	>950	>1000	>975
	°F		>1740	>1740	>1800	>1790
Volume Resistivity	ohm-cm	25°C/77°F	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$
		300°C/570°F	$2.0x10^{12}$	$2.0x10^{12}$	$1.0x10^{12}$	$2.0x10^{11}$
		600°C/1110°F	$4.6x10^{8}$	$5.2x10^{8}$	$2.3x10^{10}$	$6.0x10^{8}$
		900°C/1650°F	$3.5x10^{6}$	$4.1x10^{6}$	$5.0x10^{8}$	$2.5x10^{6}$

Property	Unit	AL-500			AL-600			AL-300			AL-995		
Dielectric Constant (K')		25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C
	10MHz	9.07	9.53	9.91	9.30	9.65	10.10	9.53	9.91	10.14	9.58	9.92	10.20
	1000MHz	9.04	—	—	9.20	—	—	9.00	—	—	9.30	—	—
	8500MHz	8.98	9.26	9.40	9.16	9.30	9.45	9.04	9.32	9.54	9.37	9.61	9.82
Dissipation Factor (Tan δ)		25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C
	10MHz	0.00026	0.00028	0.00341	0.00030	0.00061	0.00330	0.00004	0.00016	0.00052	0.00003	0.00009	0.00040
	1000MHz	0.00062	—	—	0.00044	—	—	0.00030	—	—	0.00014	—	—
	8500MHz	0.00078	0.00155	0.00155	0.00062	0.00085	0.00121	0.00045	0.00040	0.00072	0.00009	0.00014	0.00025
Loss Factor (K' Tan δ)		25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C	25°C	300°C	500°C
	10MHz	0.00236	0.00267	0.03369	0.00279	0.00588	0.03333	0.00038	0.00158	0.00527	0.00029	0.00089	0.00408
	1000MHz	0.00560	—	—	0.00405	—	—	0.00270	—	—	0.00130	—	—
	8500MHz	0.00700	0.01165	0.01457	0.00568	0.00719	0.01143	0.00407	0.00373	0.00687	0.00084	0.000135	0.00245

APPENDIX A: MATERIAL PROPERTY TEST DATA

FIGURES

FMC Corporation

Corporate Technology Center
1205 Coleman Avenue
Box 580
Santa Clara California 95052
408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 930177

FMC

January 29, 1993

RESULTS OF TESTING
ASTM D695
COMPRESSIVE STRENGTH

SERIAL NUMBER 4648I1102544-3

Specimen Number	Ultimate Compressive Strength (lbs)	Ultimate Compressive Strength (psi)
1	12,767	260,028
2	20,638	420,326
3	20,393	415,336
4	14,877	302,994
5	17,466	355,723
6	21,455	436,965
7	20,953	426,741
8	21,089	429,511
9	21,546	438,819
10	18,994	386,843

Test rate - 10,000 pounds/minute
Room temperature
Overall specimen length - 0.500 inch, Specimen diameter - 0.250 inch

Tested by: [signature]

Figure A-1. Compressive strength test data for cylinder part 544-3.

FMC Corporation

Corporate Technology Center
1205 Coleman Avenue
Box 580
Santa Clara California 95052
408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 930177

FMC

January 29, 1993

RESULTS OF TESTING
Federal Standard 1492 (4-point)
FLEXURAL STRENGTH

Serial No.: 464811102544-3

Specimen Number	Load at Failure (lbs)	Modulus of Rupture (psi)
1	123.2	39443
2	143.5	45942
3	123.4	39507
4	133.0	42580
5	139.4	44629
6	132.2	42324
7	143.7	46006
8	136.9	43829
9	135.4	43349
10	134.9	43189
11	141.4	45270
12	134.9	43189
13	133.8	42837
14	138.4	44309
15	131.1	41972
16	138.4	44309
17	139.3	44597
18	136.1	43573
19	134.6	43093
20	141.5	45302

Test rate - 0.02 inch/minute
Room temperature
Overall specimen length - 2.000 ± 0.050 inch
Specimen breadth - 0.250 inch
Specimen depth - 0.125 inch

Tested by: [signature]

Figure A-2. Flexural strength test data for cylinder part 544-3.

TEST DATE - 2/11/93 L/N 930117

VELOCITY/MODULUS WORKSHEET

Sample I.D.	Thickness (inches)	Density (g/cm3)	Density (lb/in3)	No of Echoes Longitudinal	Distance 1st to nth echo	Longitudinal Velocity (In/sec)	No of Echoes Transverse	Distance 1st to nth echo	Transverse Velocity (In/sec)	Young's Modulus E - (Mpsi)
Calibration Standards (Knowns).										
Longit.	0.1001	N/A	N/A	9	2.568	234300	N/A	N/A	N/A	N/A
Trans.	0.2529	N/A	N/A	N/A	N/A	N/A	7	2.350	235037	N/A
544-3										
1	0.2493	3.7565	0.13569	6	2.348	425467	7	2.328	233881	49.31
2	0.2492	3.7566	0.13570	6	2.348	425297	7	2.345	232092	48.73
3	0.2495	3.7584	0.13576	6	2.346	426172	7	2.347	232174	48.82
4	0.2488	3.7562	0.13568	6	2.325	428814	7	2.348	231424	48.69
5	0.2499	3.7578	0.13574	6	2.350	426128	7	2.338	233441	49.22
6	0.2499	3.7562	0.13568	6	2.335	428866	7	2.364	230873	48.51
7	0.2497	3.7498	0.13545	6	2.342	427242	7	2.348	232261	48.80
8	0.2493	3.7569	0.13571	6	2.325	429676	7	2.348	231889	48.89
544-4										
1	0.2500	3.7567	0.13570	6	2.378	421279	7	2.357	231652	48.37
2	0.2506	3.7547	0.13563	6	2.366	424432	7	2.360	231913	48.60
3	0.2504	3.7560	0.13567	6	2.363	424632	7	2.364	231335	48.44
4	0.2500	3.7559	0.13567	6	2.352	425936	7	2.345	232837	48.99
5	0.2506	3.7555	0.13566	6	2.369	423895	7	2.352	232701	48.83
6	0.2505	3.7542	0.13561	6	2.383	421236	7	2.353	232510	48.61
7	0.2508	3.7547	0.13563	6	2.361	425670	7	2.361	231999	48.69
8	0.2507	3.7549	0.13563	6	2.363	425141	7	2.351	232893	48.95

PA 7MM700515 Page 1 Tested by:

Figure A-3. Density and compressive modulus data for cylinder parts 544-3 and 544-4.

FMC Corporation

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Box 580
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408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 930177

FMC

January 29, 1993

RESULTS OF TESTING
ASTM D695
COMPRESSIVE STRENGTH

SERIAL NUMBER 4648I1019544-4

Specimen Number	Ultimate Compressive Strength (lbs)	Ultimate Compressive Strength (psi)
1	21,678	441,507
2	21,634	440,611
3	20,382	415,112
4	19,785	402,953
5	20,579	419,124
6	18,481	376,395
7	18,389	374,521
8	20,059	408,534
9	20,730	422,200
10	21,004	427,780

Test rate - 10,000 pounds/minute
Room temperature
Overall specimen length - 0.500 inch; Specimen diameter - 0.250 inch

Tested by:

Figure A-4. Compressive strength test data for cylinder part 544-4.

FMC Corporation

Corporate Technology Center
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Santa Clara California 95052
408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 930177

FMC

January 29, 1993

RESULTS OF TESTING
Federal Standard 1492 (4-point)
FLEXURAL STRENGTH

SERIAL NO.: 464811019544-4

Specimen Number	Load at Failure (lbs)	Modulus of Rupture (psi)
1	141.8	45398
2	134.5	43061
3	128.5	41140
4	141.7	45366
5	129	41300
6	138	44181
7	139.4	44629
8	138.1	44213
9	140.7	45046
10	139.1	44533
11	138.3	44277
12	134.9	43189
13	132.4	42388
14	140.3	44918
15	139.4	44629
16	124.8	39955
17	135.1	43253
18	122.1	39091
19	139.2	44565
20	140.4	44950

Test rate - 0.02 inch/minute
Room temperature
Overall specimen length - 2.000 ± 0.050 inch
Specimen breadth - 0.250 inch
Specimen depth - 0.125 inch

Tested by Robert J. Krog

Figure A-5. Flexural strength test data for cylinder part 544-4.

FMC Corporation

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408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 93-188

FMC

RESULTS OF TESTING
ACMA Test #1
COMPRESSIVE STRENGTH

Serial No: 4649F0315649-4

Specimen Number	Ultimate Compressive Strength (lbs)	Diameter	Area	Ultimate Compressive Strength (psi)
1	21,502	0.25	0.0491	438,000
2	20,297	0.25	0.0491	413,500
3	20,272	0.25	0.0491	413,000
4	19,448	0.25	0.0491	396,200
5	19,078	0.25	0.0491	388,700
6	19,455	0.25	0.0491	396,300
7	20,546	0.25	0.0491	418,600
8	19,272	0.25	0.0491	392,600
9	20,301	0.25	0.0491	413,600
10	20,730	0.25	0.0491	422,300
			Average	409,300
			Standard Deviation	14,700

Test rate - 10,000 pounds/minute
Room temperature
Overall specimen length - 0.500 inch; Specimen diameter - 0.250 inch

Tested by: B Kipp
B. Kipp

May 13, 1993
PA 7MM7-011-15

2

Figure A-6. Compressive strength test data for Type 4 hemisphere part 649-4.

FMC Corporation

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Santa Clara California 95052
408 289 2731

MATERIALS ENGINEERING
RESULTS RECORD NO. 93-188

FMC

RESULTS OF TESTING
Federal Standard 1492 (4-point)
FLEXURAL STRENGTH

Serial No: 4649F0315649-4

Specimen Number	Load at Failure (lbs)	Modulus of Rupture (psi)
1	158	50,584
2	162	51,865
3	146	46,742
4	166	53,145
5	161	51,545
6	163	52,185
7	170	54,426
8	172	55,066
9	153	48,984
10	159	50,904
11	131	41,940
12	165	52,825
13	143	45,782
14	157	50,264
15	156	49,944
16	143	45,782
17	171	54,746
18	150	48,023
19	162	51,865
20	155	49,624
	Average	50,300
	Std Deviation	3,300

Test rate - 0.02 inch/minute
Room temperature
Overall specimen length - 2.000 ± 0.050 inch
Specimen breadth - 0.250 inch
Specimen depth - 0.125 inch

Tested by: B. Kipp
B. Kipp

May 13, 1993
PA 7MM7-011-15

Figure A-7. Flexural strength test data for Type 4 hemisphere part 649-4.

Lab No.: 930934

TEST DATE: 5/12/93

VELOCITY/MODULUS WORKSHEET

Charge No.: 7MM701115

Sample Identification.	Material Thickness (inches)	Material Density (g/cm3)	Material Density (lb/in3)	No of Echoes Longitudinal	Distance 1st to nth echo (inches)	Longitudinal Velocity (in/sec)	No of Echoes Transverse	Distance 1st to nth echo (inches)	Transverse Velocity (in/sec)	Young's Modulus E - (Mpsi)
Calibration Standards (Knowns).										
Longit.	0.1001	N/A	N/A	10	2.162	234300	N/A	N/A	N/A	N/A
Trans.	0.2529	N/A	N/A	N/A	N/A	N/A	9	2.473	235037	N/A
Batch No. 4649F0315649-4										
#1	0.2498	3.7376	0.13501	7	2.292	386073	9	2.517	228098	44.79
#2	0.2500	3.7490	0.13542	7	2.269	390299	9	2.505	229374	45.59
#3	0.2496	3.7399	0.13509	7	2.268	389846	9	2.486	230757	45.81
#4	0.2497	3.7485	0.13540	7	2.280	387950	9	2.497	229833	45.52
#5	0.2503	3.7465	0.13533	7	2.268	390940	9	2.510	229192	45.56
#6	0.2498	3.7380	0.13502	7	2.277	388617	9	2.497	229925	45.47
#7	0.2502	3.7481	0.13539	7	2.261	391993	9	2.513	228827	45.56
#8	0.2504	3.7391	0.13506	7	2.294	386663	9	2.515	228827	45.04

Performed By: Jm 3/17/ TW

Page 1

FORM-E494-Rev 3-3/15/93

Figure A-8. Density and compressive modulus data for Type 4 hemisphere part 649-4.

FMC Materials Engineering Laboratories
1205 Coleman Avenue ◆ Box 580 ◆ Santa Clara, CA 95052

TEST REPORT

ACMA Test #1
COMPRESSIVE STRENGTH

Serial No: 4744F0624755-4

Specimen Number	Ultimate Compressive Load (lbs)	Diameter (in.)	Area (sq. in.)	Ultimate Compressive Strength (psi)
1	18,041	0.25	0.0491	367,500
2	16,357	0.25	0.0491	333,200
3	17,525	0.25	0.0491	357,000
4	19,854	0.25	0.0491	404,500
5	13,584	0.25	0.0491	276,700
6	18,785	0.25	0.0491	382,700
7	17,767	0.25	0.0491	361,900
8	19,404	0.25	0.0491	395,300
9	19,466	0.25	0.0491	396,600
10	15,785	0.25	0.0491	321,600

Average: 359,700
Std. Deviation: 37,800

Test rate - 10,000 pounds/minute
Room temperature
Overall specimen length - 0.500 inch; Specimen diameter - 0.250 inch

Analyst: R. Kipp
Approved:

For more information about FMC's Materials Engineering Laboratories services, call (408) 289-0215

Figure A-9. Compressive strength test data for Type 6 hemisphere part 755-4.

FMC Materials Engineering Laboratories
1205 Coleman Avenue ◆ Box 580 ◆ Santa Clara, CA 95052

TEST REPORT

Page 1

CUSTOMER:	Paula Davis	CUST. PO NO:	14652
COMPANY:	WESGO, Inc.	FMC ACCT. NO:	7MM7-015-15
REPORT DATE:	September 15, 1993	FMC LAB NO:	931634

Federal Standard 1492 (4-point)
FLEXURAL STRENGTH

Serial No: 4744F0624755-4

Specimen Number	Load at Failure (lbs)	Modulus of Rupture (psi)
1	164	52,505
2	156	49,944
3	155	49,624
4	149	47,703
5	147	47,063
6	169	54,106
7	141	45,142
8	147	47,063
9	175	56,027
10	176	56,347
11	164	52,505
12	142	45,462
13	151	48,343
14	165	52,825
15	153	48,984
16	156	49,944
17	157	50,264
18	158	50,584
19	157	50,264
20	161	51,545

Average: 50,300
Std. Deviation: 3,000

Test rate - 0.02 inch/minute
Room temperature
Overall specimen length - 2.000 ± 0.050 inch
Specimen breadth - 0.250 inch
Specimen depth - 0.125 inch

Analyst: R. Kipp
Approved: L. Ravi

For more information about FMC's Materials Engineering Laboratories services, call (408) 289-0215

Figure A-10. Flexural strength test data for Type 6 hemisphere part 755-4.

Lab No.: 931634

TEST DATE: 1/14/93

VELOCITY/MODULUS WORKSHEET

Charge No.: 7MM7-015-15

Sample Identification.	Material Thickness (inches)	Material Density (g/cm3)	Material Density (lb/in3)	No of Echoes Longitudinal	Distance 1st to nth echo (inches)	Longitudinal Velocity (in/sec)	No of Echoes Transverse	Distance 1st to nth echo (inches)	Transverse Velocity (in/sec)	Young's Modulus E - (Mpsi)
Calibration Standards (Knowns).										
Longit.	0.1001	N/A	N/A	10	2.150	234300	N/A	N/A	N/A	N/A
Trans.	0.2529	N/A	N/A	N/A	N/A	N/A	7	2.148	235037	N/A
4744F0624755-4										
#1	0.2503	3.7527	0.13555	7	2.128	414347	7	2.144	233055	48.35
#2	0.2508	3.7537	0.13559	7	2.136	413619	7	2.136	234395	48.72
#3	0.2505	3.7323	0.13482	7	2.136	413125	7	2.149	232698	47.90
#4	0.2504	3.7522	0.13554	7	2.150	410271	7	2.142	233365	48.17
#5	0.2506	3.7539	0.13560	7	2.141	412324	7	2.149	232791	48.15
#6	0.2502	3.7528	0.13556	7	2.133	413210	7	2.131	234383	48.68
#7	0.2504	3.7517	0.13552	7	2.142	411803	7	2.150	232497	48.00
#8	0.2504	3.7525	0.13555	7	2.136	412960	7	2.149	232605	48.12

Performed By: [signature]

Page 1

FORM-E494-Rev 3-3/15/93

Figure A-11. Density and compressive modulus data for Type 6 hemisphere part 755-4.

APPENDIX B: DIMENSIONAL RANGE DATA FORMS

FIGURES

WESGO Technical Ceramics and Brazing Alloys

HEET ____ OF ____

DIMENSIONAL RANGE DATA FORM

PURCHASE ORDER NO.	PART NAME	S.O.
N66001-92-C-0030	Housing, Cylindrical 25"	125601
DRAWING NUMBER (GRAPHIC)	ISSUE	LOT#
55910-0127-544 -3	Rev. B	3A4648 I 1102

DRAWING DIMENSION OR NOTE		RANGE MIN.	RANGE MAX.	SAMPLE SIZE
1. 31.90 ± .010		31.9025	31.9033	
2. .90 ± .010		.899	.9218	
3. Ø 25.000 ± .005		24.999	25.0014	
4. R. .04 ± .010 4PL.		.032	.048	
5. ⊥ .010 A		.0005	.001	
6.				
7. -A- ▱ .002		6	∠.001	
8.				
9. // .010 ▱ .002 A		.0005 Ø	.001 ∠.001	
10.				
11. 63√ 2PL.		35	45	
12.				
13. 16√ 2PL.		5	8	
14.				
15. Serial # 25C544003				
16.				
17. Visual Class A	W/I Spec			
18. Candling	No Visual			
19. Porosity	Defects Observed			
20.				

Contract # N66001-92-C-0030

Item # 0001 Code # 944

3061
INSPECTOR

(8-76)

L. Davis
QUALITY ASSURANCE

4/2/93
DATE COMPLETED

Figure B-1. Dimensional range data form for cylinder part 544-3.

SHEET ____ OF ____

DIMENSIONAL RANGE DATA FORM

WESGO Technical Ceramics and Brazing Alloys

PURCHASE ORDER NO.	PART NAME	S.O.
N66001-92-C-0030	Housing, Cylindrical 25"	125601
DRAWING NUMBER (GRAPHIC)	ISSUE	LOT#
55910-0127-544 - 4	Rev. B	3A4648 I 1019

DRAWING DIMENSION OR NOTE		RANGE MIN.	RANGE MAX.	SAMPLE SIZE
1. 31.90 ± .010		31.9067	31.9072	
2. .90 ± .010		.902	.9065	
3. Ø 25.000 ± .005		25.0023	25.0039	
4. R. .04 ± .010 4PL.		.032	.050	
5. ⊥ .010 A		.001	.003	
6.				
7. -A- ▱ .002		0	<.001	
8.				
9. // .010 ▱ .002 A		.0005 0	.001 <.001	
10.				
11. 63√ 2PL.		24	35	
12.				
13. 16√ 2PL.		7	12	
14.				
15. Serial # 25C544004				
16.				
17. Visual Class A	W/I Spec			
18. Candling	No Visual Defects			
19. Porosity	observed			
20.				

Contract # N66001-92-C-0030

Item # 0001 Code # 944

C. Pusel — INSPECTOR

P. Davis — QUALITY ASSURANCE

3/26/93 — DATE COMPLETED

Figure B-2. Dimensional range data form for cylinder part 544-4.

WESGO
Technical Ceramics
and Brazing Alloys

SHEET 1 OF 1

DIMENSIONAL RANGE DATA FORM

PURCHASE ORDER NO.	PART NAME	S.O.
N66001-92-C-0030	CERAMIC HEMI, TYPE 4 BATTERY HOUSING	125603
DRAWING NUMBER (GRAPHIC)	**ISSUE**	LOT# 5A4649
55910-0127-649	B	EC315

DRAWING DIMENSION OR NOTE		RANGE MIN.	RANGE MAX.	SAMPLE SIZE
1. Ø 25.000 ± .005/.015		24.9975	24.999	
2. Ø 23.200 ± .015/.005		23.195	23.196	
3. ⊕ Ø .000 Ⓛ A B Ⓛ		.001	.002	
4. -A- ▱ .002		6	<.001	
5. 2.50 ± .01		2.526	2.528	*
6. SPHER R 11.86		11.851	11.854	
7. ⊕ Ø .000 Ⓛ A B Ⓛ		.001	.003	
8. SPHER R 12.59		12.596	12.599	
9. ⊕ Ø .000 Ⓛ A B Ⓛ		.001	.003	
10. R 4.00 +2.00/.00		3.5	3.8	
11. R .04 ± .01		.030	.040	
12. 15° ± ½°		15°5'	15°17'	
13. 3.13 ± .010		3.000	3.053	*
14. 16 ∇		6	14	
15. 63 ∇ APL		40	55	
16. SERIAL NO.				
17. 25H649004	25H649 004			
18. VISUAL CLASS A	W/I Spec			
19. CANDLING	No Defects			
20. POROSITY	Observed			

Contract# N66001-92-C-0030 Item # 0001AC Code # 944. Notes: (1) 3.13" DIMENSION IS UNDERSIZE (2.90") AND ALSO THE WIDTH OF THE 15° TAPER. WE BELIEVE THIS CONDITION COULD BE FIXED IF WE SET-UP TO RE-GRIND AND MOVING THE CENTER LINE OF THE GRINDING WHEEL PATH RELATIVE TO THE PART. (2) MARKINGS IN I.D. IS ONLY COSMETIC. WE USED A BOWLING BALL TO MEASURE WALL THICKNESS & IN THE PROCESS THE BALL MARKED THE I.D. OF THE HEMI.

3061
INSPECTOR

QUALITY ASSURANCE

7/16/93
DATE COMPLETED

Figure B-3. Dimensional range data form for Type 4 hemisphere part 649-4.

SHEET 1 OF 2

DIMENSIONAL RANGE DATA FORM

WESGO Technical Ceramics and Brazing Alloys

PURCHASE ORDER NO.	PART NAME	S.O.
N66001-92-C-0030	Ceramic Hemi Type 6 Battery Housing	125604
DRAWING NUMBER (GRAPHIC)	ISSUE	LOT# 3A 4744
55910-0127-755	B	1-0624

DRAWING DIMENSION OR NOTE		RANGE MIN.	RANGE MAX.	SAMPLE SIZE
1. Ø 25.000 ± .002/.013		25.000	25.005	
2. Ø 23.200 ± .015/.005		23.200	23.205	
3. ⊕ Ø .000 Ⓛ A B Ⓛ		0	.005	
4. -A- ⏥ .002		Ø	<.001	
5. 2.50 ± .01		2.460	2.575	
6. SPHER R 11.86		11.860	11.862	
7. ⊕ Ø .000 Ⓛ A B Ⓛ		Ø	.006	
8. .563 ± .010		.568	.569	
9. R 4.00 ± 2.00/.00		2.6	3.8	
10. R .04 ± .01		.035	.040	
11. 15° ± ½°		15°	15°10"	
12. 3.13 ± .010		3.095	3.205	
13. 2.003 ± 2.005		2.0037	2.005	
14. ⊕ Ø .040 Ⓢ A B Ⓢ		Ø	.020	
15. 1.003 / 1.005		1.004	1.006	
16. ⊕ Ø .040 Ⓢ A B Ⓢ		Ø	.018	
17. R .030 ± .02		.015	.018	
18. 90° ± ½°		90°	90°	
19. 16 ✓ 3PL	Faces / Holes	8 / 18	12 / 22	
20. 63 ✓ 2 PL		20	36	

Contract# N66001-92-C-0030 Item# 0001AD Code # 944

NOTE: AFTER INVESTIGATING THE CAUSE FOR MISSING THE 2.50 ±.01 SPEC I CONCLUDED THAT THE HEMI TILTED WHILE BLANCHARD GRINDING ABOUT .010" THIS CAUSED THE FACE TO GO OUT of SQUARE BY .058" AS MEASURED ON THE VARIATION of THE 2.46 - 2.575. [signature] 10/26/93

3072 — INSPECTOR (6.78)

[signature] — QUALITY ASSURANCE

10/25/93 — DATE COMPLETED

Figure B-4. Dimensional range data form for Type 6 hemisphere part 755-4, sheet 1.

SHEET 2 OF 2

DIMENSIONAL RANGE DATA FORM

WESGO Technical Ceramics and Brazing Alloys

PURCHASE ORDER NO.	PART NAME	S.O.
N66001-92-C-0030	Ceramic Hemi Type 6 Battery Housing	125604
DRAWING NUMBER (GRAPHIC)	ISSUE	LOT# 3A 4744
55910-0127-649	B	F0624

DRAWING DIMENSION OR NOTE		RANGE MIN.	RANGE MAX.	SAMPLE SIZE
1. SERIAL NO.				
2. 25B755 004				
3. VISUAL CLASS A	w/i Spec			
4. CANDLING	No DefecTs			
5. POROSITY	Observed			
6.				
7.				
8.				
9.				
10.				
11.				
12.				
13.				
14.				
15.				
16.				
17.				
18.				
19.				
20.				

Contract# N66001-92-C-0030 Item # 0001AD Code # 944

3072
INSPECTOR

L. Davis
QUALITY ASSURANCE

10/25/93
DATE COMPLETED

Figure B-4. Dimensional range data form for Type 6 hemisphere part 755-4, sheet 2.

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Fifth Generation Housings, Part I

5. FUNDING NUMBERS

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PROJ: S0397
ACC: DN302232

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13. ABSTRACT *(Maximum 200 words)*

An unmanned undersea vehicle external pressure housing was designed for ocean depths of 20,000 feet (9,000 psi) using 96-percent alumina ceramic for the major hull components. The pressure housing assembly, with an outside diameter of 26 inches and an overall length of 91 inches, consists of two alumina cylindrical bays joined by a central stiffening titanium joint ring with forward and aft alumina hemispherical end closures. The exterior of the housing is protected with a spectra fiber reinforced epoxy composite fairing.

The alumina-ceramic components of the housing assembly successfully withstood proof testing to 10.000 psi (1.1 times the design operating pressure). The forward and aft head end closures also completed 500 cycles to 9,000 psi without catastrophic failure. The 26-inch diameter housing assembly has a dry weight of 876 pounds and displaces 1,496 pounds when submerged in sea water, resulting in a net lift of 620 pounds. The net lift generated by the alumina ceramic housing assembly is approximately three times greater than the net lift that would be achieved by an equivalent rib-stiffened titanium housing assembly designed to the same operational requirements.

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UNCLASSIFIED

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R. P. Johnson	(619) 553-1935	Code 564

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Standard form 298 (BACK)

UNCLASSIFIED

THE AUTHORS

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RAMON R. KURKCHUBASCHE is a Research Engineer for the Ocean Engineering Division and has worked since November 1990 in the field of deep submergence pressure housings fabricated from ceramic materials. His education includes a B.S. in Structural Engineering from the University of California at San Diego, 1989; and an M.S. in Aeronautical/Astronautical Engineering from Stanford University in 1990. His experience includes conceptual design, procurement, assembly, testing, and documentation of ceramic housings. Other experience includes buoyancy concepts utilizing ceramic, nondestructive evaluation of ceramic components. He is a member of the Marine Technology Society, and has published "Elastic Stability Considerations for Deep Submergence Ceramic Pressure Housings," *Intervention '92*, and "Nondestructive Evaluation Techniques for Deep Submergence Housing Components Fabricated from Alumina Ceramic," *MTS '93 Proceedings.*

DR. JERRY STACHIW is Staff Scientist for Marine Materials in the Ocean Engineering Division. He received his undergraduate engineering degree from Oklahoma State University in 1955 and graduate degree from Pennsylvania State University in 1961.

Since that time he has devoted his efforts at various U.S. Navy Laboratories to the solution of challenges posed by exploration, exploitation, and surveillance of hydrospace. The primary focus of his work has been the design and fabrication of pressure resistant structural components of diving systems for the whole range of ocean depths. Because of his numerous achievements in the field of ocean engineering, he is considered to be the leading expert in the structural application of plastics and brittle materials to external pressure housings.

Dr. Stachiw is the author of over 100 technical reports, articles, and papers on design and fabrication of pressure resistant viewports of acrylic plastic, glass, germanium, and zinc sulphide, as well as pressure housings made of wood, concrete, glass, acrylic plastic, and ceramics. His book on "Acrylic Plastic Viewports" is the standard reference on that subject.

For the contributions to the Navy's ocean engineering programs, the Navy honored him with the Military Oceanographer Award and the NCCOSC's RDT&E Division honored him with the Lauritsen-Bennett Award. The American Society of Mechanical Engineers recognized his contributions to the engineering profession by election to the grade of Life-Fellow, as well as the presentation of Centennial Medal, Dedicated Service Award and Pressure Technology Codes Outstanding Performance Certificate.

Dr. Stachiw is past-chairman of ASME Ocean Engineering Division and ASME Committee on Safety Standards for Pressure Vessels for Human Occupancy. He is a member of the Marine Technology Society, New York Academy of Science, Sigma Xi and Phi Kappa Honorary Society.